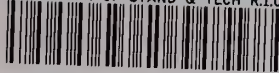


Reference

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Measurements on Insulating Materials at Cryogenic Temperatures

William E. Anderson and Richard S. Davis

Electrosystems Division
Center for Electronics
and Electrical Engineering
National Bureau of Standards

August 1979
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Final Report

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U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, *Secretary*

Luther H. Hodges, Jr., *Deputy Secretary*

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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Abstract

This final report describes the results of a four-year effort to study the high voltage dielectric behavior of various materials at cryogenic temperatures. Dissipation factors at 60 Hz were measured for polymer tapes and epoxy samples at 4.2 K, atmospheric pressure. Multi-layer polymer samples in coaxial geometries at temperatures from 7 to 10 K and helium pressures up to 1.5 megapascals were also studied. The measurements were performed at stresses up to 40 MV/m. Since partial discharges were a major source of losses at the higher stresses and their presence was possibly detrimental to the integrity of the insulation, instrumentation was developed and implemented to study these discharges under conditions found in proposed ac superconducting power-transmission lines.

Summary

The contents of the following report are here summarized for the convenience of the reader. The report covers the period from November 1974 through October 1978.

In November of 1974 the National Bureau of Standards began a project sponsored by the then Energy Research and Development Administration to study ac losses in dielectrics at cryogenic temperatures and at high electrical stresses. The ultimate goal of the project was to provide dissipation factor and partial discharge data under the proposed operating conditions for Brookhaven National Laboratory's (BNL's) ac superconducting power-transmission line (ac SPTL). Because of BNL's urgent need for engineering data and the necessary delay involved in designing and constructing a supercritical cryostat, initial efforts were toward providing 60-Hz dissipation factor data of polymer films at 4.2 K and at atmospheric pressure. These measurements provided valuable data at the electrical stresses proposed for the ac SPTL. Dissipation factor measurements on layers of polymer films suggested that losses at interfaces may dominate the intrinsic dielectric losses of the polymer films. These interfacial losses are probably due to partial discharges. Since their effect may diminish under the proposed supercritical conditions of the actual ac SPTL, measurements were extended to more realistic conditions. A partial discharge measurement system was designed to carefully monitor the integrity of the dielectric under partial discharge conditions.

Besides the measurements on the polymer tape insulation for the BNL SPTL, dissipation factor and dielectric constant values of various epoxies were provided to Union Carbide Corporation, Linde Division (UCC-Linde). These epoxies were to be used as spacers in their liquid helium-insulated cable.

In order to accomplish the necessary measurements, two different cryogenic facilities were built. The first consisted of a conventional glass double-dewar system. High voltage was introduced into the cryostat by means of a vacuum-insulated bushing which was discharge free to 8.5 kV. All experiments were performed with the sample material immersed in liquid helium at atmospheric pressure. Size limitations of the dewar necessitated the use of a small (10 cm^2) parallel-plate capacitor as sample-holder. The second cryogenic facility consisted of a conventional stainless steel dewar with a liquid nitrogen jacket. The sample was placed in a pressure vessel which allowed measurements at pressures up to 1.5 megapascals. Polymer films were wrapped around the bare cylindrical high-voltage electrode permitting measurements in the coaxial geometry and under the temperature and pressure conditions of the proposed BNL SPTL.

Electrical measurement of dissipation factor was made by comparing the loss of the sample dielectric with that in a commercial compressed-gas high-voltage capacitor. This comparison was made with sufficient accuracy by using the NBS current-comparator bridge. Samples formed the dielectric of a three-terminal capacitor. Due to the small dissipation factor allowable in any practical superconducting cable insulation, an

accuracy of $\pm 1 \times 10^{-6}$ was desirable in the measurements. Success in this was achieved through a meticulous absolute determination of our compressed-gas high voltage capacitor.

As an initial consistency check we measured the dissipation factor of liquid helium at 4.2 K. At a stress of 1.5 kV/mm the 60 Hz dissipation factor was $(0.3 \pm 0.7) \times 10^{-6}$. This is consistent with the fact that liquid helium has no intrinsic loss mechanisms at power frequencies.

As previously mentioned initial measurements were made of single-layer films with the parallel-plate sample holder at 4.2 K and atmospheric pressure. No attempt was made to measure a representative sample of polymer tapes. Only those tapes that proved to be among the most promising from mechanical tests, low-voltage electrical tests, or economic considerations were sent to us by BNL. Each sample was measured at least twice to test repeatability and prevent erroneous values caused by the occasional cracking of some materials. The polyethylenes and polypropylenes both have dissipation factors considerably less than 30×10^{-6} (upper limit for BNL SPTL) at cryogenic temperatures and at design stresses of the order of 20 kV/mm. These films along with the polyamide sample, however, have poor mechanical properties at liquid helium temperatures. The polycarbonate and polysulfone films are much better mechanically but have dissipation factors in the range of 50 to 100×10^{-6} . An attempt by the manufacturer to improve the dissipation factor of one of these materials (green polysulfone) by reducing the concentration of sodium impurities was somewhat successful.

While the dissipation factor of most of the materials increases slightly with increasing voltage, both of the polyether-sulfone samples measured have negative voltage coefficient. We do not know whether the cause of this is related to the well-understood similar behavior of oil-impregnated paper-insulated capacitors.

The dissipation factor of the epoxies submitted by UCC-Linde were an order of magnitude larger than the polymer tapes but below the 500×10^{-6} limit for the UCC-Linde SPTL. There were inconsistencies in dissipation factor results between different thickness samples made of the same material. A model was developed that accounted for this behavior.

We found it impossible to make these single-layer atmospheric-pressure measurements without coating the electrode-sample interfaces with paraffin oil. Presumably this procedure suppresses partial discharges at the interfaces. It was observed that when samples were not coated with paraffin oil prior to insertion into the sample capacitor, the measured dissipation factor exhibited a large voltage coefficient.

To examine further the effects of paraffin oil on various interfaces, several stacking arrangements of polypropylene films were studied. We measured the dissipation factor of three-sheet stacks of this material with and without paraffin oil on the various interfaces. As the number of uncoated surfaces increased, the positive voltage coefficient of the dissipation factor increased. Since this effect may be suppressed under the supercritical conditions of the BNL proposed SPTL, our measurements were extended to these conditions.

Dissipation factor measurements on multi-layer coaxial samples under supercritical conditions were for the most part encouraging. Dissipation factors for many samples were less than 20×10^{-6} for stresses of several megavolts/meter. As the stress increased there appeared a break point or point at which the dissipation factor became strongly dependent on electrical stress. This break-point stress agreed with the measurements of others on the breakdown of supercritical helium when allowance was made for the dielectric mismatch of the polymer and the helium butt gaps. The actual BNL SPTL will contain bedding and screen layers. The screen layer was found to have little effect on the dissipation factor. Preliminary measurements with the bedding layer did indicate serious problems.

Part of the NBS program was to study the effect partial discharges might have on the electrical insulation. NBS designed and constructed a partial discharge measurement system for this purpose. The system which includes a minicomputer, measures partial discharge amplitude spectra. A change in a given spectrum would indicate that the properties of the dielectric were changing. Measurements under conditions of varying electrical stress, frequency of the applied voltage, impurity or defect concentration, temperatures, and pressures could yield important information on aging processes at cryogenic temperatures.

Only a small number of long (3 hour) measurements were made with this instrumentation yielding limited information. The effort near the end of the NBS program was redirected to providing dissipation factor

data for BNL on new materials thought to be promising. (The partial discharge measurement system recently has been used extensively on measurements of the partial discharge behavior of SF_6 at room temperatures).



Introduction

In November of 1974 the High Voltage Measurements Section in the Electricity Division of the Institute for Basic Standards (now the Applied Electrical Measurements Group in the Electrosystems Division of the Center for Electronics and Electrical Engineering) began a project sponsored by the then Energy Research and Development Administration to study ac losses in dielectrics at cryogenic temperatures. The ultimate goal of the project was to provide dissipation factor and partial discharge data for the dielectric materials under consideration for use in ac superconducting power-transmission lines (ac SPTLs). At that time there were two ac SPTLs being developed domestically. One was a rigid cable that used liquid helium for both the coolant and the dielectric. The center high voltage conductor was held in place by epoxy spacers. This cable was being developed by the Linde Division of Union Carbide Corporation (UCC-Linde). Brookhaven National Laboratory (BNL) was developing the other ac SPTL. This cable was flexible until cooled. The insulation contemplated was analogous to conventional oil-impregnated paper cables in that helium played the role of oil and a suitable polymer played the role of paper.

The early work then was involved with the measurement of the dielectric constant and dissipation factor for the insulating materials to be used in the BNL and UCC-Linde SPTLs. A group of workers at Oak Ridge National Laboratory were complementing this effort by determining the breakdown characteristics of these insulating materials under high electrical stress.

In order to provide timely data to BNL and UCC-Linde our early work was limited to measurements of thin polymer and epoxy films at atmospheric pressure and at 4.2 K. Dielectric constant and dissipation factor measurements were made up to stresses of 40 MV/m. Of the polymer tapes being considered for the BNL SPTL, several were found to have dissipation factors less than the 30×10^{-6} upper limit that BNL personnel had originally ascribed in order to minimize refrigeration load. However, when stacks of these thin polymer films were measured, their dissipation factor showed an alarmingly strong positive voltage dependence. This necessitated measurements under the operating conditions of the BNL SPTL in order to determine if the resulting higher helium densities would reduce this problem. Several epoxy samples were initially measured for UCC-Linde. Since the epoxy represented only a small fraction of the total dielectric volume in their cable, a higher dissipation factor could be tolerated. Development of this cable was curtailed and, as a result, no additional epoxy measurements were made.

Dissipation factor measurements on polymer tapes for BNL were thus extended to multi-layer coaxial geometries, 7 to 10 K temperatures, and 1.5 MPa pressures. The dissipation factors for the most part under these conditions showed far less voltage dependence than for multi-layer samples at atmospheric pressure. The voltage dependence that did occur seemed to be a result of partial discharges.

A partial discharge measurement system was developed based on the pulse-height-analysis technique to study the behavior of these tapes under the proposed operating conditions. The instrumentation is described

in an appendix to this report. The evolution of the partial discharge amplitudes as a function of time for various pressures, temperatures, electrical stresses, materials, frequencies, impurity or defect concentrations would yield important information on aging processes at these low temperatures. These measurements were never completed because of the termination of funding in September 1978.

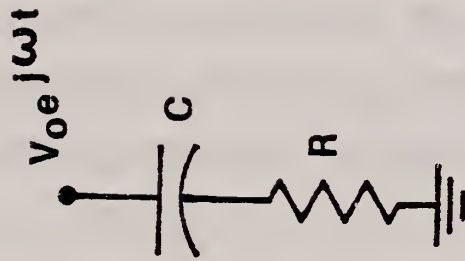
This report covers the period from November 1974 through October 1978. The work through June 1976 will be described in lesser detail as it was contained in an earlier report.^[1] Also the previous report contained a bibliography of useful references that will not be repeated here. This report is divided into three major sections: Dielectric Loss Measurement Methodology; Dielectric Loss Results and Discussion; and Partial Discharge Measurements. The appendix provides a complete description of the partial discharge measurement system developed for this project.

I. Dielectric Loss Measurement Methodology

In considering the measurement of dielectric loss, it is convenient to model the dielectric and its electrodes as a combination of an ideal capacitor and an ideal resistor. This model, in the absence of partial discharges, is adequate to explain the loss behavior of a capacitor containing a dielectric. Two equally valid configurations of capacitor and resistor are shown in Fig. 1. In general, the resistor value will be a function of the frequency and of the applied voltage. The problem of measuring dielectric loss may be thought of as equivalent to finding the value of the resistor in either Fig. 1A or 1B.

While many techniques to measure dielectric loss have been used, circumstances generally limit the optimum choice. For instance, for very lossy capacitors the test capacitor may be combined with an inductor to produce an LC circuit. The value of L which causes the circuit to resonate at a given frequency determines the value of C in Fig. 1 while the width of the resonance can be used to find R or R' . Clearly, this technique is unsuitable if the capacitor's loss is less than that of the inductor.

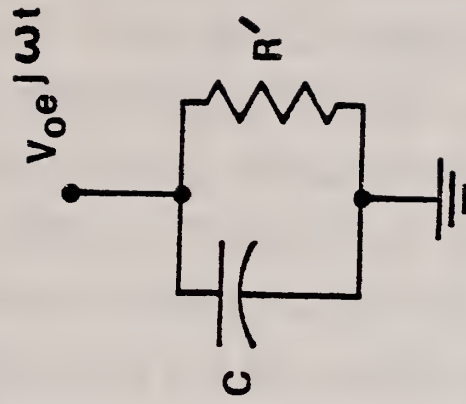
Two techniques have been successfully applied to the measurement of dielectric loss at cryogenic temperatures. One of these techniques depends on the fact that current through the resistor of Fig. 1 is shifted



$$I = \frac{V_0}{1/j\omega C + R}$$

$$\tan \delta = \omega CR$$

A.



$$I = V_0(j\omega C + 1/R')$$

$$\tan \delta = 1/\omega CR'$$

B.

FIGURE 1 Model of capacitor with dielectric loss.

by 90 ° with respect to capacitive current. In the case of Fig. 1A,

$$I = \frac{(\omega^2 C^2 R + j\omega C) V_0}{1 + \omega^2 C^2 R^2} \quad \text{and in the case of Fig. 1B, } I = V_0 \left(\frac{1}{R} + j\omega C \right).$$

The angle by which the total current vector differs from the vector for a pure capacitor is known as δ . The tangent of δ (or $\tan \delta$) is a figure of merit for dielectric materials. This number is also known as the "dissipation factor", or "D.F.". In Fig. 1A, $\tan \delta = \omega CR$; in Fig. 1B, $\tan \delta = \frac{1}{\omega CR}$. For any good dielectric material $\tan \delta$ is small. If the dielectric constant of a material is written in terms of its real and imaginary parts, i.e., $\epsilon = \epsilon' + j\epsilon''$ where ϵ' and ϵ'' are real numbers, then $\tan \delta = \frac{\epsilon''}{\epsilon'}$. One can use ac bridge techniques to balance the two current components against known standards of capacitance and resistance and thereby determine $\tan \delta$. This is the technique we have used. It will be discussed in detail within this report.

A second technique, which has been successfully applied to the measurement of single dielectric sheets at cryogenic temperatures, measures $\tan \delta$ using a calorimetric method. The power dissipated in a capacitor in the form of heat is $P = I \cdot V = \omega CV^2 \tan \delta$. If the heat capacity of the sample and holder can be determined and is small, a measurement of temperature rise can be used to find $\tan \delta$. This technique was pioneered in England by Vincett.^[2] It has been used successfully in this country by King and Thomas.^[3] Calorimetric measurements have proven to be extremely useful for studying intrinsic dielectric behavior

at 4 K over a wide range of frequency. The technique is, however, not well suited to measurements of composite dielectric structures such as actual cables because of the large heat capacities involved.

We have thus far assumed that the $\tan \delta$ losses are independent of the applied voltage. It was further assumed that whatever be the source of the dielectric loss, it causes no deterioration of the material. At a high enough voltage, partial discharges begin to be observed and the above two assumptions are no longer valid. No cable is designed to operate in the partial discharge regime. Nevertheless, it is important that partial discharges be examined because unplanned circumstances may temporarily force the cable into partial discharge. Techniques for the study of partial discharges in the cryogenic cable models will be presented later in this report.

Dissipation Factor Measurements

We have measured $\tan \delta$ for various samples at cryogenic temperatures by using a current comparator bridge operating at 60 Hz. The details of the electronic instrumentation will be described below. Common to every capacitance bridge technique is the balancing of an unknown capacitance against a known standard. The unknown or sample capacitor contains the dielectric to be measured. Thus, ideally, the sample capacitance is determined by a combination of the capacitor dimensions and the dielectric constant of the material filling the capacitor. The $\tan \delta$ of the capacitor depends only on the sample dielectric. We used two sample capacitors in the course of our measurements. One, constructed at NBS, was in the form of

parallel plates and was designed for measurements of single sheets of dielectric material. The other, given to us by Brookhaven National Laboratory, was a mandrel designed for the simulation of the composite dielectric and coaxial geometry used in cryogenic cables of the BNL design.

A. Parallel Plate Sample Holder

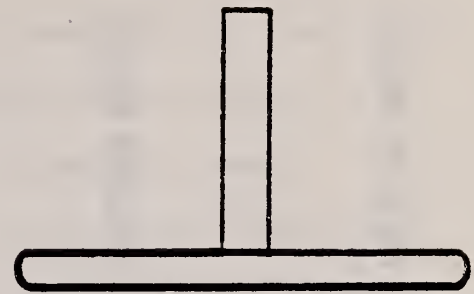
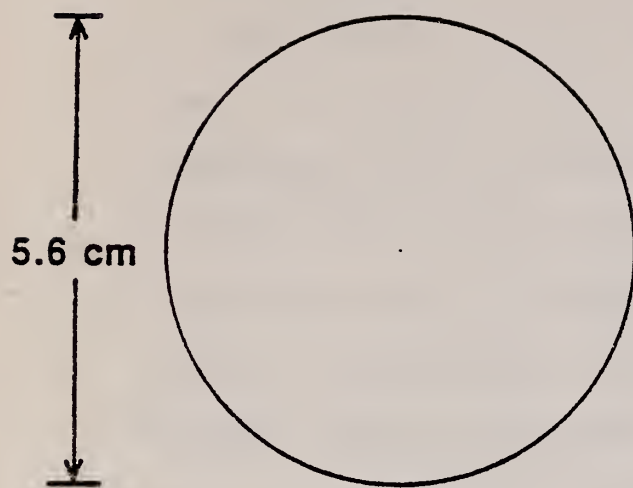
The sample holder consists of the two plates forming the parallel-plate capacitor, the dielectric of which is the material to be measured. The stainless-steel electrodes are shown in Fig. 2. The bottom plate consists of an active (inner) electrode and a guard ring. These two electrodes were epoxied together then lapped and polished. The area of the active electrode is $1.05 \times 10^{-3} \text{ m}^2$ resulting in the following relation between capacitance C and thickness d (in μm) of the dielectric:

$$C \approx 9.29 \times 10^3 (\epsilon'/d) \text{ picofarads.} \quad (1)$$

Typical thickness of the sample dielectric ranged from 25 μm to 125 μm so that the capacitances to be measured are in the range of about 100 to 1000 pF ($\epsilon' \sim 2$ or 3 for proposed polymer insulation).

The capacitor is held together with two polytetrafluorethylene plates using nylon screws and nuts with phosphor-bronze springs as shown in Fig. 3. During the actual measurement the top electrode is energized and the resulting current from the inner, active electrode is sent to the current comparator bridge via a coaxial cable. The outer shield of the cable is connected to the guard ring on the one end and to ground at the bridge.

TOP ELECTRODE



BOTTOM ELECTRODES

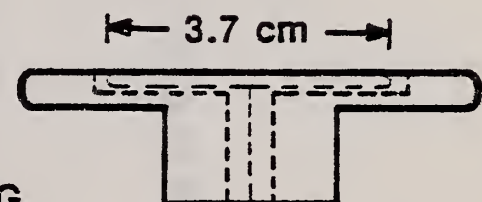
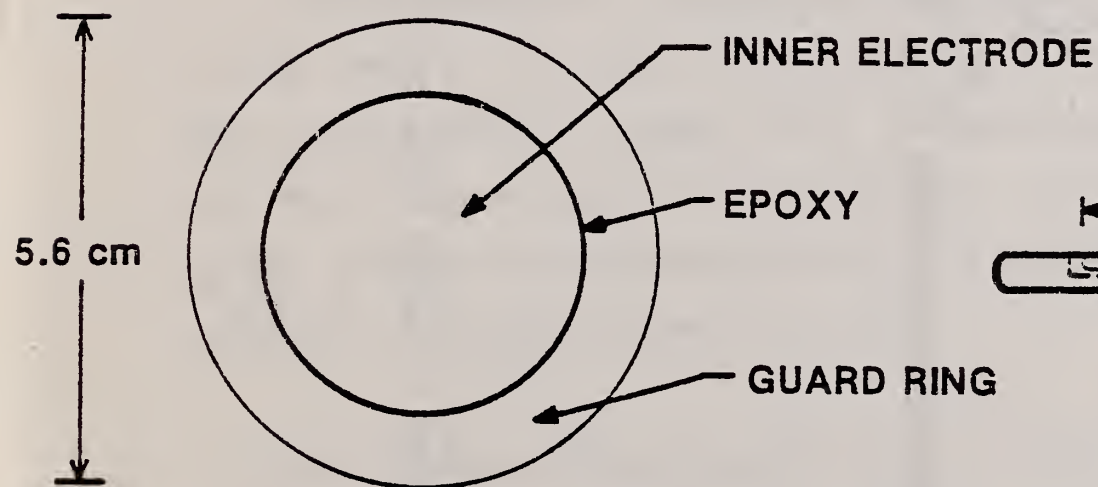


FIGURE 2 Electrodes for parallel plate sample holder.

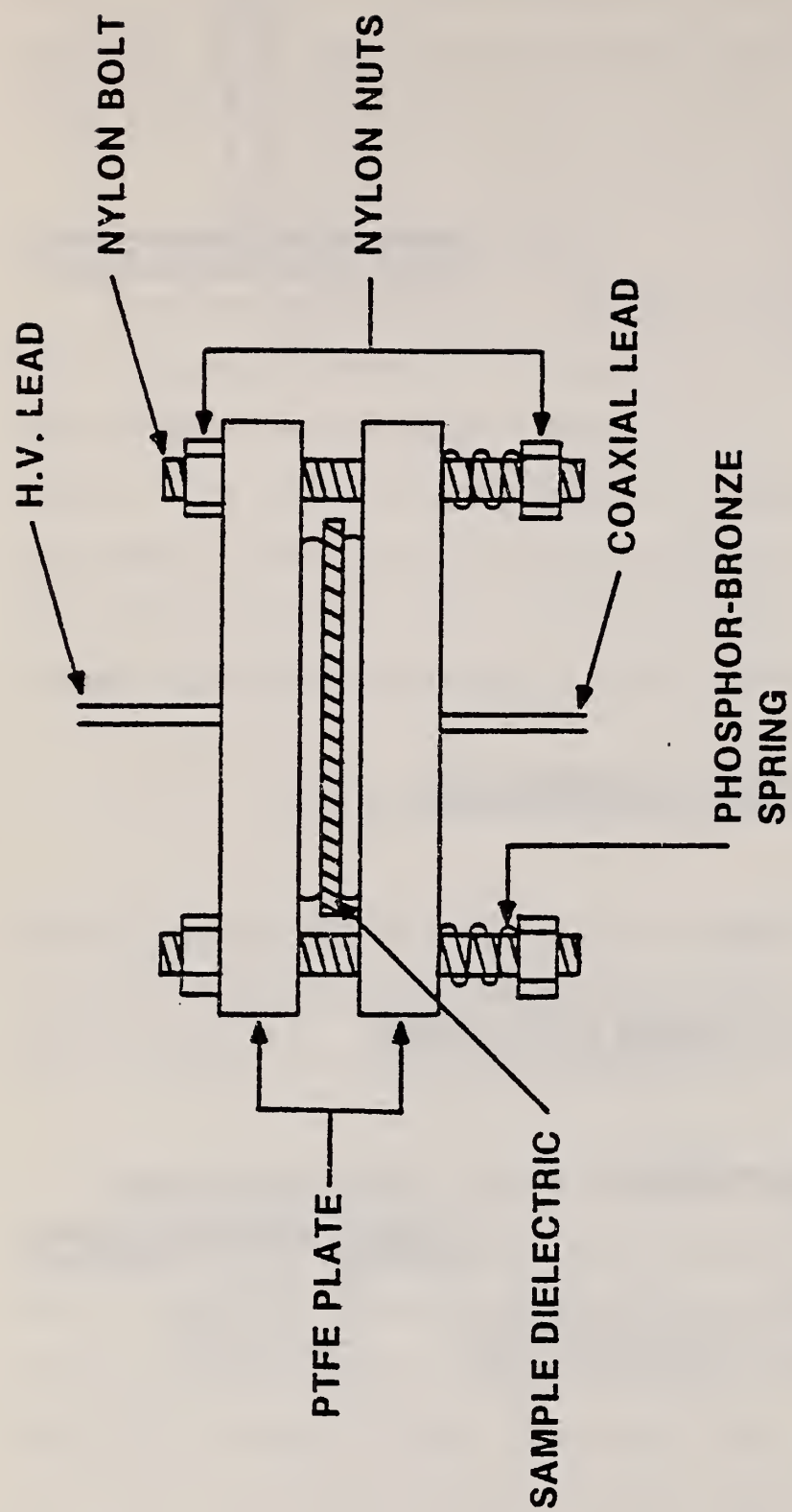


FIGURE 3 Sample holder for parallel plate measurements.

B. Cryostat

The cryostat is shown in Fig. 4. The inner diameter of the inner glass dewar is 11 cm with a usable height of 1 m. A high-vacuum electrical feedthrough ($\sim 10^{-5}$ Pa) terminated at both ends by commercial ceramic bushings (rated at 8.5 kV rms) was used to get the high voltage below the liquid helium level. This was necessary because gaseous helium has poor breakdown characteristics (several times worse than air). A stainless steel, shielded, coaxial cable brings the low-voltage signal out of the liquid helium to the top of the cryostat. The total resistance of the leads running from the capacitor to the bridge was less than 1 Ω . At 60 Hz, this resistance would cause an added dissipation factor 1×10^{-6} in the measurement of a 2600 pF capacitor. Since the capacitances of all samples measured in this apparatus were substantially less than this, the lead resistance is seen to have a negligible effect on the measurement of dissipation factor.

A typical measurement required about 5 to 6 liters of liquid helium allowing from 3 to 4 runs per 25 liter supply dewar. The helium would remain in the cryostat for several hours, if necessary, although most measurements were completed in less than an hour. The time for the cryostat to cycle from room temperature to 4.2 K and back to room temperature was about 20 hours which allowed daily runs.

Since the dewars are constructed of glass, no attempt was made to measure the dissipation factor as a function of increasing helium pressure. Also in these measurements the sample was immersed directly in liquid

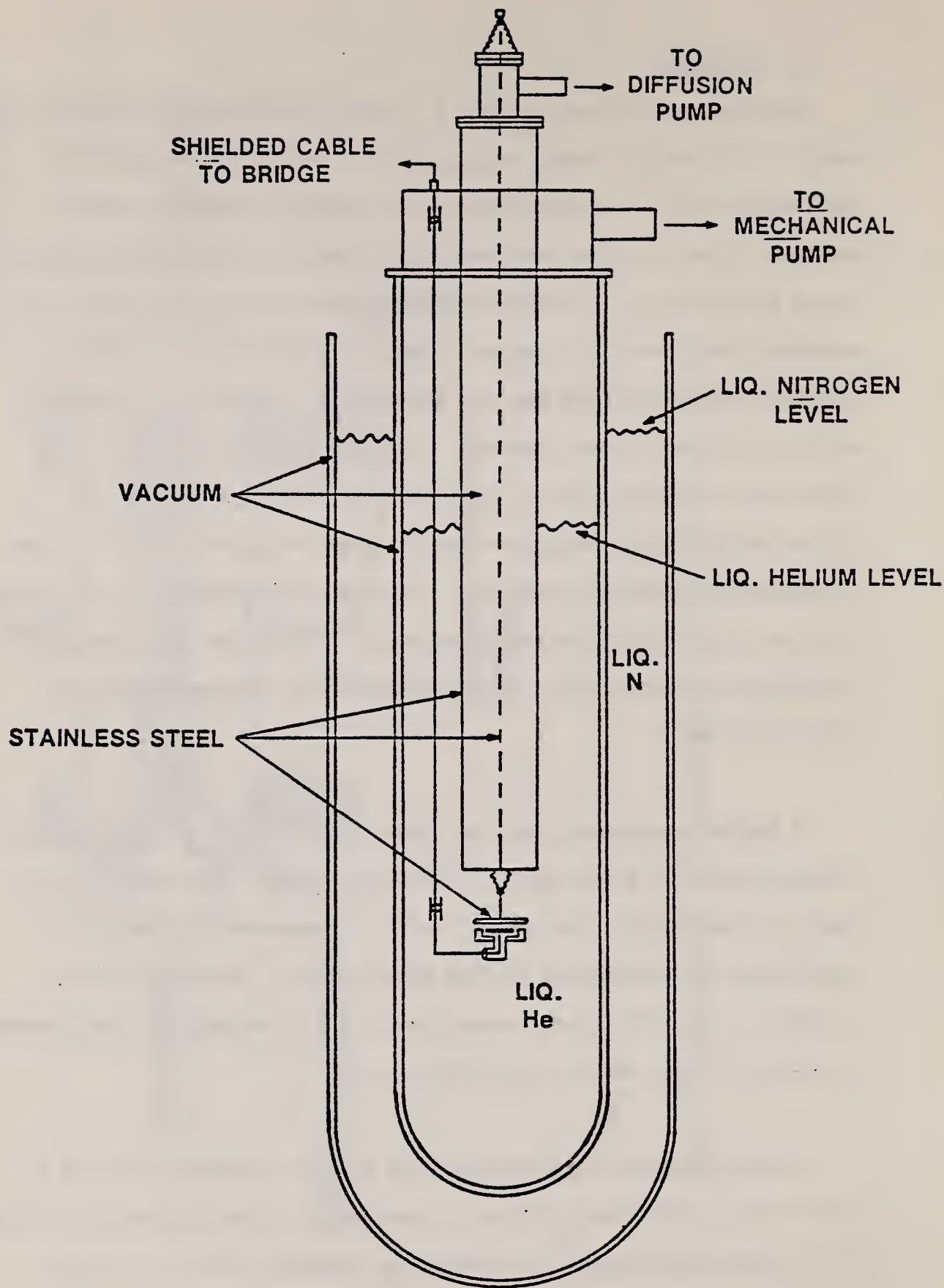


FIGURE 4 Cryostat for parallel-plate measurements.

helium while in the calorimetric measurements of King and Thomas^[3], the sample was in a vacuum.

C. Mandrel and Associated Cryostat for Coaxial Measurements

In order to test selected tapes at conditions more nearly simulating the BNL cable design than those of our parallel-plate sample holder, we acquired, in October 1976, apparatus developed by BNL. The apparatus consisted of a cryostat specially designed to accommodate mandrels around which were wound plastic tapes in simulation of cable insulation. These mandrels were also designed and built by BNL personnel. In addition, BNL provided us with a tapewinding device with which it was possible to wind layers of tape on a mandrel at selectable pitch angles. Although the cryostat and mandrel facility have been described in detail by their designers^[4], it will be useful to restate the features of this facility which were most important to our work and to detail our own modifications to the equipment. The mandrels terminated in stress-relief cones at either end. The bare portion of the mandrel was a cylinder of ~ 50 cm in length and 1.3 cm in diameter. The mandrels could be mounted vertically in the cryostat at which time the bare portion of the mandrel was centered along the vertical axis of the cryostat. The inner chamber of the cryostat was 5 cm in diameter. The stress-relief cones of the mandrels allowed one to energize the center electrode to at least 50 kV without the onset of corona. In addition, the cryostat was designed to withstand helium pressures of over 10^6 Pa at temperatures from 4 K to 10 K. The cryostat was housed in a liquid-nitrogen jacketed, stainless-steel helium dewar identical to that used at BNL.

Extensive modifications of the mandrels were necessary before they could be used for D.F. measurements. At BNL, the mandrels were used for breakdown studies. Therefore, the center electrode was simply energized and the cryostat grounded. On the other hand, D.F. measurements of the precision required by this project require that the sample holder be a three-terminal capacitor. What is more, the low voltage and guard electrodes must only be grounded at the current comparator bridge. These problems were solved in the following way.

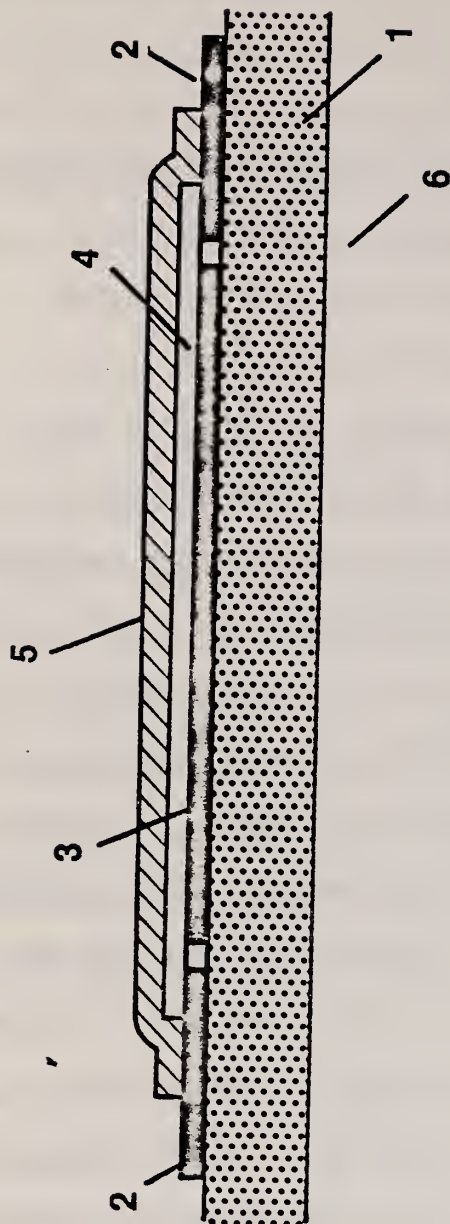
First, a shallow groove was machined along the mandrel insulation from the point at which it enters the cryostat to the point at which it begins to taper toward the bare center electrode. A shielded cable (made of an insulated wire in a stainless-steel tube) was cemented into the groove with epoxy. The top of the cable was terminated with a BNC connector. It was found that upon cooling, shrinkage of the polytetrafluoroethylene insulation in the connector sometimes caused a leak to the pressurized cryostat. Replacement of a small segment of the insulation with epoxy solved this problem.

A second groove machined along the mandrel insulation provided space for thermometer leads. For our three-terminal measurements it was possible to introduce thermometers directly into the inner chamber of the cryostat instead of relying on thermometers placed in the vacuum space surrounding the inner chamber as was done at BNL.

At first, germanium resistance thermometers were used, but it was found that these were not robust enough to withstand repeated cycling to pressures of many atmospheres. Instead, calibrated carbon resistors were used and proved to be nearly ideal.

Pressure in the cryostat was read using a Bourdon-tube type aneroid barometer. A somewhat less accurate transducer was also used as a check. The mandrels were wound on the tape-winding machine that we obtained from BNL. This machine allows the pitch angle to be easily varied. Figure 5 (a cross-sectional view parallel to the axis) shows how the mandrels were wound and illustrates the guarding arrangement that is necessary with the NBS current comparator bridge. The connection to the stainless steel coaxial cable, mentioned above, is not shown. The tape to be measured (Valeron* in Fig. 5) was first wound on the mandrel with the proper registration and tension. The low voltage electrode and the two guard electrodes were then attached. The inner wire of the stainless-steel coaxial cable was soldered to the low voltage electrode (the active electrode), and this electrode and wire were then covered with a layer of insulation. Another guard, electrically attached to the two guard electrodes and the outer conductor of the stainless-steel coaxial cable, was placed over this insulation. A final layer of insulation (not shown) was then wound around the outer guard to isolate it electrically from the pressure vessel wall.

Under these conditions, the capacitance in picofarads of a measured sample is



1. 4 LAYERS OF VALERON, 65-35 REGISTRATION
2. GUARD ELECTRODES (tin)
3. LOW VOLTAGE ELECTRODE (tin)
4. 1 LAYER OF INSULATION, OVERLAPPED
5. SHIELD (tin)
6. HIGH VOLTAGE ELECTRODE (stainless steel)

FIGURE 5 Cross-section of mandrel showing wound layers.

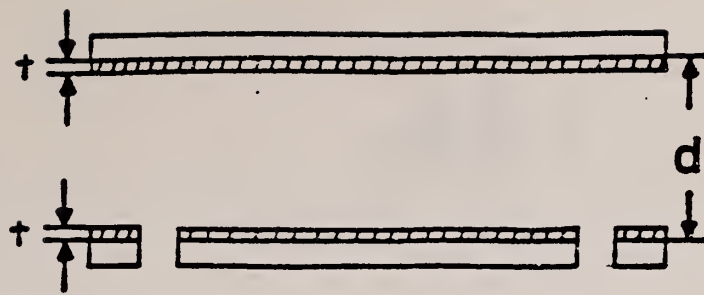
$$C \approx \frac{8.85 \epsilon' L}{\ln r_2/r_1},$$

where L is the length of the active electrode in meters, r_1 is the radius of the inner electrode (mandrel) and r_2 is the distance from the center axis of the mandrel to the active outer electrode. The quantity ϵ' is an effective value for the composite structure of polymer tapes and helium-filled butt gaps.

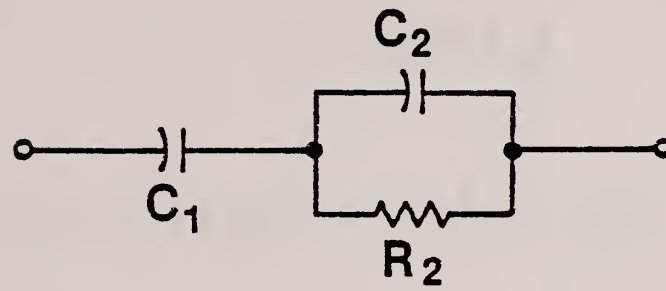
D. Standard Capacitor

Since the dielectric properties of the sample are obtained by electrically balancing the current in the sample capacitor with the current in the standard capacitor, a knowledge of the properties of the standard capacitor is essential for this measurement. A 100 pF compressed-gas (nitrogen) capacitor was used for the standard. In the majority of high voltage measurements, this type of capacitor can be assumed to be lossless. (Commercial capacitors generally claim a dissipation factor of "less than 10×10^{-6} "). In our measurements, where a total dissipation factor uncertainty of $\pm 1 \times 10^{-6}$ was necessary, the dissipation factor of the standard capacitor must be accurately measured. The current comparator bridge which will be described in the next section has the capability of measuring relative dissipation factors to better than $\pm 1 \times 10^{-6}$ but the absolute dissipation factor of the standard must be known in order to determine the dissipation factor of the material being measured. The dissipation factor of our standard capacitor was measured by John Q. Shields of the Center for Absolute Physical Quantities, NBS. A brief discussion of how this was done^[5,6] follows.

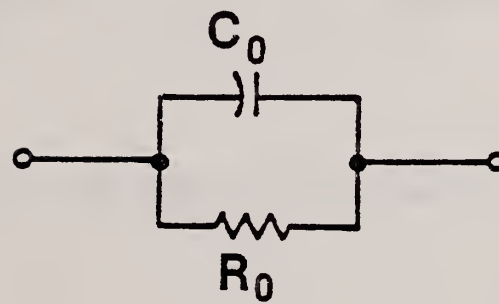
A guard ring capacitor with variable plate separation is placed in one arm of a transformer ratio-arm bridge and the standard capacitor to be measured in the other. Successive relative dissipation factor balances between the variable capacitor at different plate settings and the standard capacitor with auxiliary capacitors in parallel with it are made. Since the relative dissipation factors between the standard capacitor and each of the auxiliary capacitors can readily be measured, then the relative dissipation factor between the standard and the variable plate capacitor at several settings will be known. If the dissipation factor for the variable plate capacitor is caused only by a surface film, a plot of the relative dissipation factor versus capacitance should be on a straight line as will be shown below. The guard-ring capacitor with electrode spacing, d , and film thickness, t , is shown in Fig. 6a. This capacitor can be represented by an ideal capacitor, C_1 , in series with a lossy capacitor with capacitance, C_2 , and parallel resistance, R_2 , Fig. 6b. This series combination can be represented as in Fig. 6c by an ideal capacitor, C_0 , in parallel with a resistor, R_0 .



a.



b.



c.

FIGURE 6 Guard-ring capacitor.

$$Y_0 = \frac{Y_1 Y_2}{Y_1 + Y_2} \quad (2)$$

where

$$Y_1 = j\omega C_1 \quad (3)$$

$$Y_2 = 1/R_2 + j\omega C_2 \quad (4)$$

and

$$Y_0 = 1/R_0 + j\omega C_0 \quad (5)$$

From (2), (3), (4), and (5),

$$Y_0 = j\omega C_1 (1 + j\omega C_2 R_2) / (1 + j\omega R_2 (C_1 + C_2))$$

or

$$Y_0 = \frac{\omega^2 C_1^2 R_2 + j\omega C_1 [1 + \omega^2 C_2 R_2^2 (C_1 + C_2)]}{1 + \omega^2 R_2^2 (C_1 + C_2)^2} \quad (6)$$

Using (5) and (6)

$$R_0 = \frac{1 + \omega^2 R_2^2 (C_1 + C_2)^2}{\omega^2 C_1^2 R_2}$$

and

$$C_0 = C_1 [1 + \omega^2 C_2 R_2^2 (C_1 + C_2)] / [1 + \omega^2 R_2^2 (C_1 + C_2)^2].$$

The dissipation factor, D.F., is equal to $(\omega C_0 R_0)^{-1}$.

$$\text{D.F.} = \omega C_1 R_2 / [1 + \omega^2 C_2 R_2^2 (C_1 + C_2)]$$

where

$$C_1 = \frac{\epsilon_0 A}{d - 2t}$$

and

$$C_2 = \frac{\epsilon_r \epsilon_0 A}{2t}$$

assuming an area, A , and dielectric constant ϵ_r for the film.

Since $t \ll d$ or $C_1 \ll C_2$

$$\text{D.F.} \approx \omega R_2 \epsilon_0 A / [(d - 2t) (1 + \omega^2 C_2^2 R_2^2)]$$

or

$$\text{D.F.} \approx \frac{K}{d - 2t} \quad (7)$$

where for a particular frequency K is a constant independent of plate spacing.

The film thickness t is much less than the electrode spacing so (7) can be further approximated

$$D.F. \approx K/d.$$

Therefore, if the dissipation factor is caused by surface films, the D.F. should vary inversely with the electrode separation, d , and hence be proportional to the capacitance. A plot of relative dissipation factor for the variable capacitor versus capacitance should be on a straight line. The intercept of this line with the dissipation factor axis represents the relative dissipation factor for infinite electrode separation and, therefore, the dissipation factor of the standard capacitor. The fact that the points do lie on a straight line supports this model.

A portable standard capacitor was calibrated in this fashion and found to have a 60-Hz dissipation factor of -1.1×10^{-6} with an uncertainty of $\pm 0.3 \times 10^{-6}$. Our compressed-gas standard capacitor had a relative dissipation factor of 2.9×10^{-6} with respect to this portable standard or an absolute dissipation factor of $1.8 \times 10^{-6} \pm 0.5 \times 10^{-6}$.

The negative dissipation factor, seemingly worrisome, is easily explained. To see how this is possible, consider Fig. 7. The three-terminal measurement of a guarded lossless capacitor, C_s , is shown in Fig. 7a.

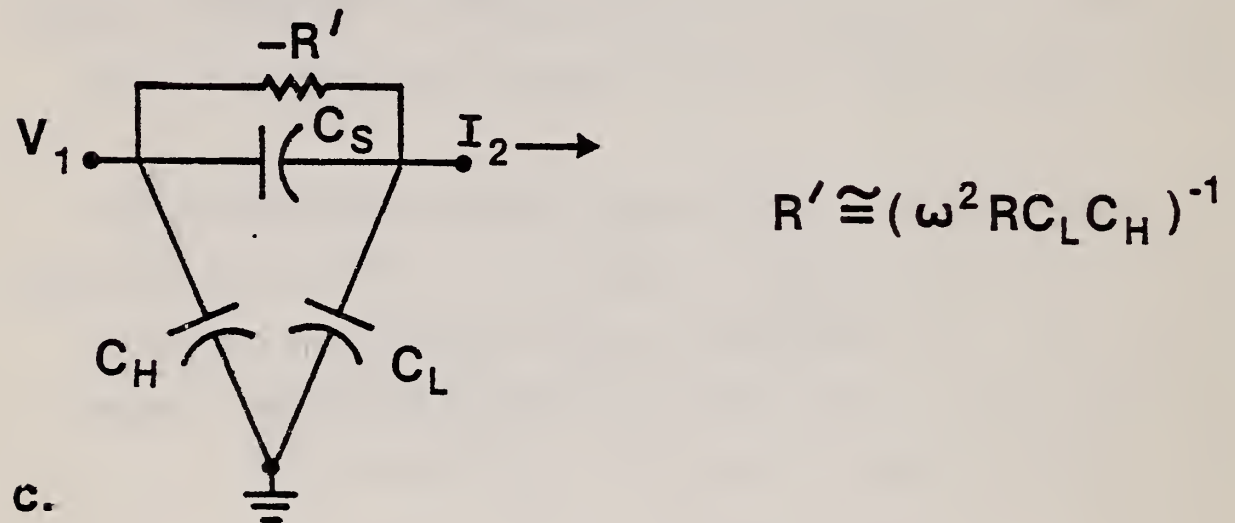
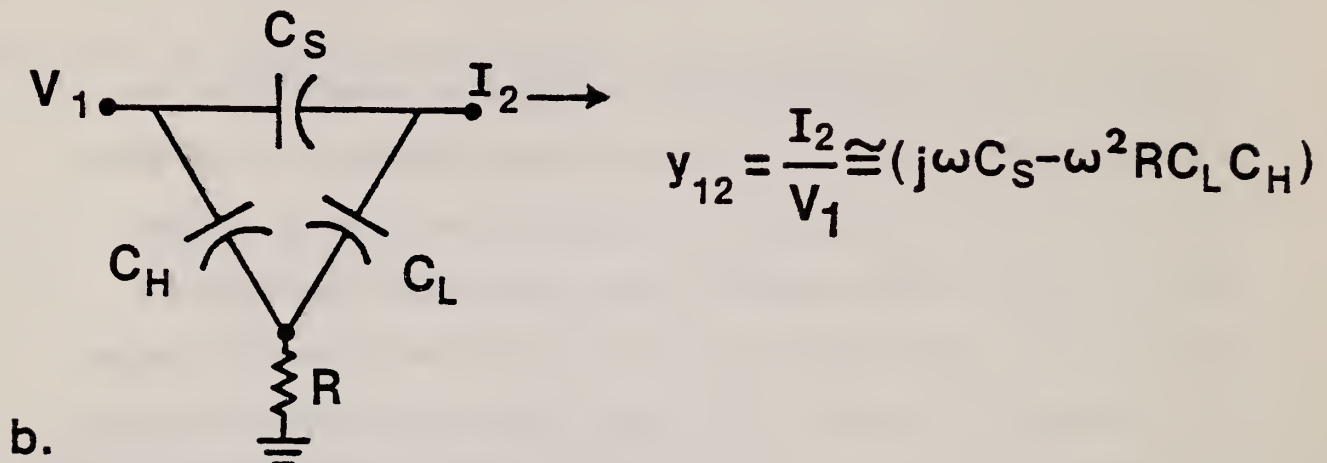
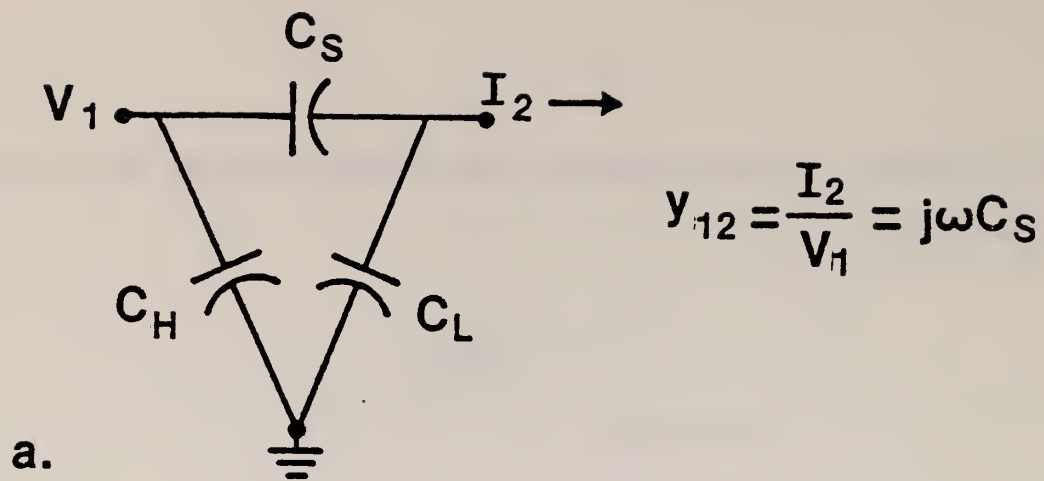


FIGURE 7 Three-terminal capacitor with negative dissipation factor.

Capacitors C_H and C_L are the capacitances formed by the guard and the high and low voltage electrodes. In a bridge measurement, the low voltage side is grounded. In this case, the short-circuit transfer admittance of the circuit shown in Fig. 7a is $y_{12} = j\omega C_S$. Now suppose, as in Fig. 7b, the capacitor's construction is flawed by loss in a common ground return. This frequency-dependent mechanism is represented by a resistance, R . If $1/R\omega$ is large, compared to both C_H and C_L , then $y_{12} \approx j\omega C_S - \omega^2 R C_H C_L$. The right hand side of this relation differs from the ideal case by containing a small term which is $\pi/2$ radians out of phase with $j\omega C_S$. Since the measurement of y_{12} is made on a "black box", the results of the measurement could be caused either by the circuit in Fig. 7b or Fig. 7c. Fig. 7c is the schematic representation of a guarded capacitor with capacitance C_S and dissipation factor equal to $-1/\omega C_S R'$ where $R' = (\omega^2 R C_H C_L)^{-1}$. The dissipation factor is negative. In the case of our portable standard capacitor, the negative dissipation factor was caused by the unsuspected presence of a layer of a high-loss adhesive between the guard and ground.

Measuring the loss of a capacitor containing liquid helium as its dielectric provided an independent means of checking the loss of our standard. At low enough voltages a liquid helium capacitor should be lossless -- the helium itself has no loss mechanisms and its temperature, 4.2 K, reduces to insignificance the loss of any adventitious film on the electrode surface.^[7] Our parallel-plate sample holder with 100 μm dielectric spacers between the guard ring and the active electrode was

used as a liquid helium capacitor. The results of a bridge measurement against our compressed-gas standard confirmed loss measurements of the standard described above. (At a stress of 1.5 kV/mm the 60 Hz dissipation factor was $(0.3 \pm 0.7) \times 10^{-6}$).

E. Current Comparator Bridge

The real part of the dielectric constant and the dissipation factor of a sample are measured by balancing the current in the sample capacitor against the current in the standard capacitor using a bridge. A simplified version of how this is done is illustrated in Fig. 8. The lossy sample capacitor is represented by a parallel combination of an ideal capacitor, C_X , and a resistor, R_X . At balance (i.e., zero signal at the detector, D) since $I_X N_X = I_S N_S$,

$$C_X = n_{sd} n_{dx} C_S$$

and

$$D.F. = (\omega R_S C_S)^{-1}$$

where

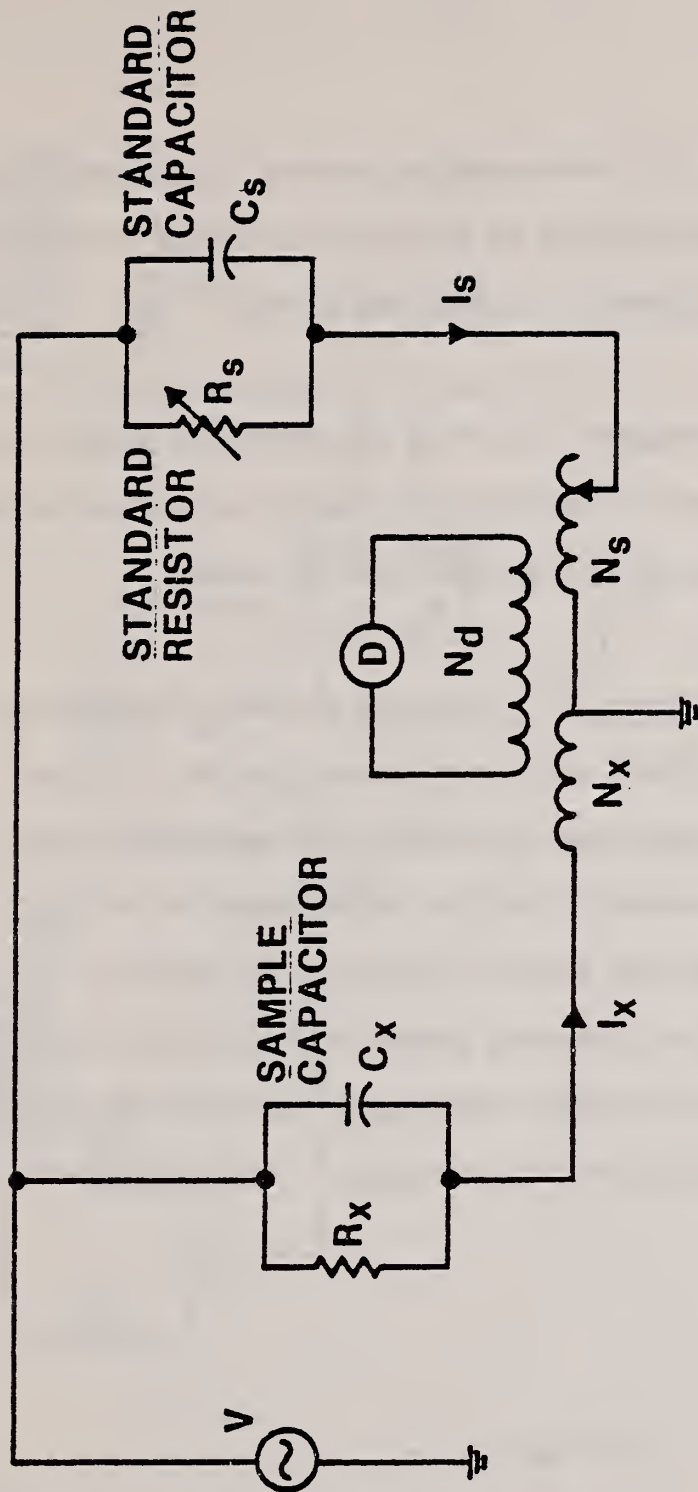


FIGURE 8 Simplified current comparator bridge.

$$n_{sd} \equiv N_s/N_d.$$

The transformer in Fig. 8 is a three-winding current transformer or a current comparator. Extensive work on this type of bridge has been done at the National Research Council in Canada and at NBS. [8,9]

Unfortunately, the bridge in Fig. 8 is not practical because resistance standards for high voltage are impractical to make, and another method for balancing the in-phase or loss current must be sought.

The circuit in Fig. 9 provides a suitable method for balancing the loss component. An operational amplifier, which provides a virtual ground for the current through the N_s winding (the amplifier's open loop gain being greater than 10^4), outputs a voltage signal equal to $-V C_s/C_f$, typically one thousandth of the source voltage, V , or smaller. A variable resistance which is connected between the amplifier output and the third current-carrying ratio winding, N_3 (opposite in polarity to N_s) can be used to balance the loss component. The balance equation now becomes:

$$C_X = n_{sd} n_{dx} C_s \quad (8)$$

$$D.F. = (N_3/N_s) (1/\omega C_f R_s). \quad (9)$$

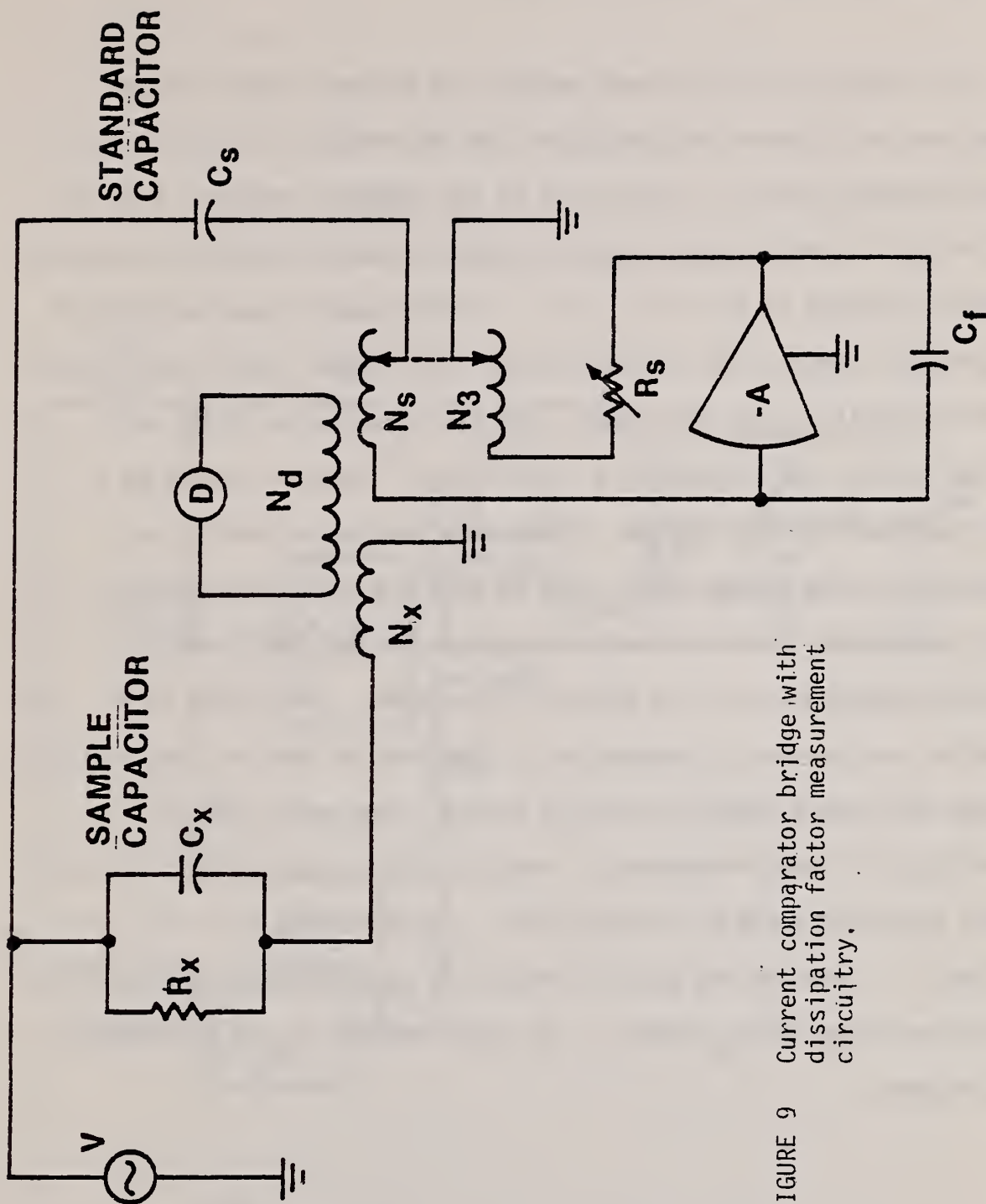


FIGURE 9 Current comparator bridge with dissipation factor measurement circuitry.

In the actual bridge the switches for the N_3 and N_S windings are mechanically coupled so that the bridge can be made direct reading in dissipation factor for a particular frequency (e.g., 60 Hz).

The resistance of the leads between the voltage source and the capacitors and between the capacitors and the bridge will contribute to the dissipation factor. In the case of the standard capacitor side of the bridge, it would take a lead resistance of about 25 ohms to cause an apparent decrease in D.F. of 1×10^{-6} . On the sample capacitor side of the bridge, however, the lead resistance could become significant. From (1) the capacitance for the sample capacitor could be as large as 1000 pF so that an increase in D.F. of 1×10^{-6} would be caused by a lead resistance of 2 to 3 ohms. The actual lead resistance in our measuring circuit is less than 1 ohm so that the lead resistance is still negligible. Larger capacitance sample holders would require careful consideration of the effect of the leads. The bridge in Fig. 10 remedies this problem by automatically compensating for the lead resistance between the sample capacitor and the bridge. The small voltage, v , caused by this lead resistance, r , results in the voltage drop across the sample capacitor being $V-v$ instead of V . To compensate for this, the voltage v is inverted and passed through the capacitor, C'_S , the resulting current entering the N_S winding. The total current in the N_S winding then becomes

$$I_S = Vj\omega C_S - vj\omega C'_S$$

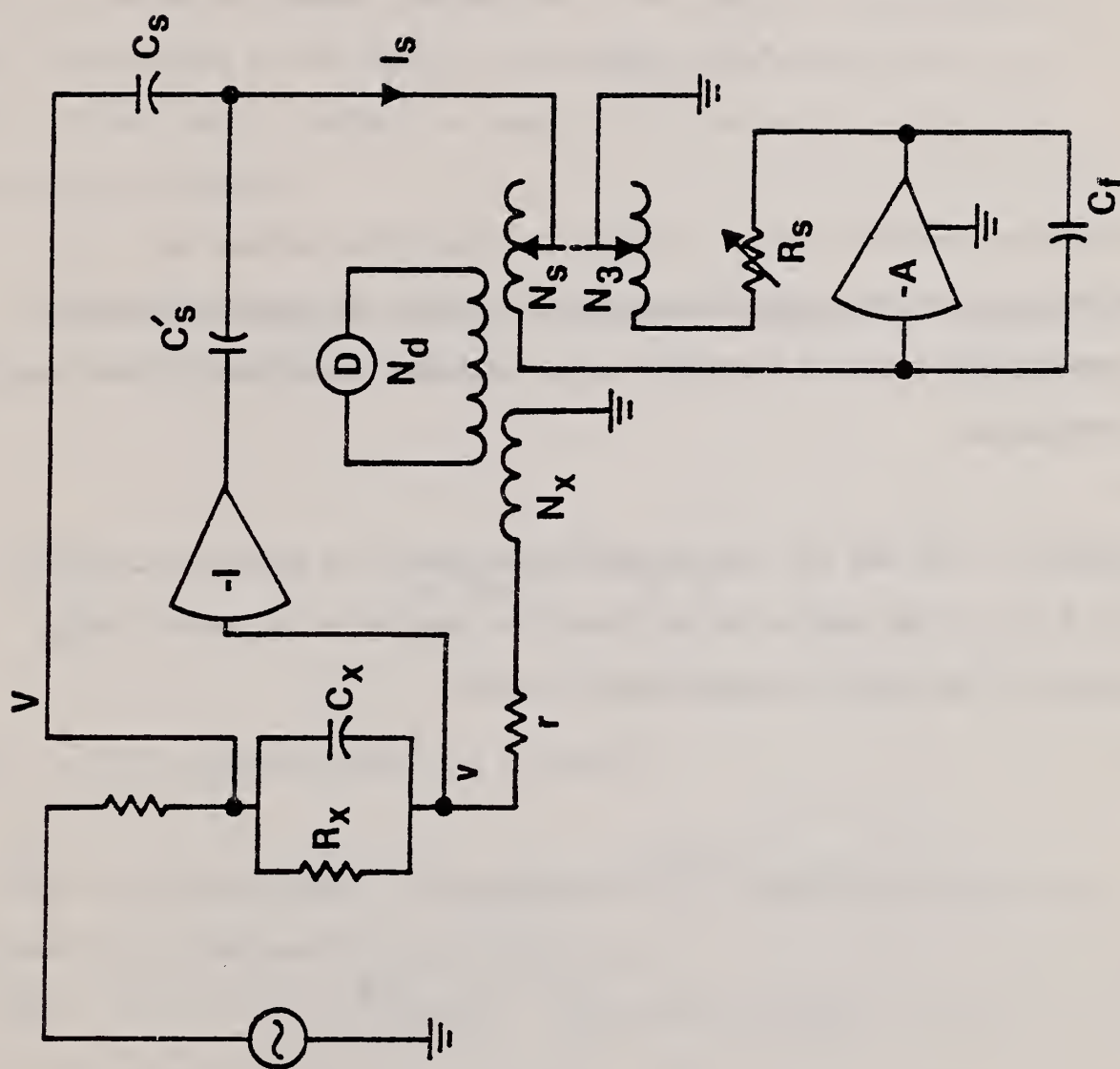


FIGURE 10 Current comparator bridge with lead compensation.

or

$$I_S = j\omega C_S (V - vC'_S/C_S).$$

If C'_S is set equal to C_S , then

$$I_S = j\omega C_S (V-v).$$

The resulting current is as if a voltage $V-v$ was placed across the standard capacitor, the same voltage that is across the sample capacitor. The compensating circuit, therefore, has eliminated the effect of this lead resistance.

From (1), (8) and (9) the dielectric-constant, ϵ' , and the dissipation factor, D.F., of the sample can be found from the bridge by the following equations for the parallel-plate sample holder:

$$\epsilon' = (1.08 \times 10^{-4}) (d n_{sd} n_{dx} C_S) \quad (10)$$

$$\text{D.F.} = (N_3/N_S) (1/\omega C_f R_S) + 1.8 \times 10^{-6} \quad (11)$$

where C_S is in picofarads and d is in micrometers.

The effect of the dissipation factor of the standard capacitor discussed in the previous section is included in (11).

The estimated uncertainty of (11) is $\pm 1 \times 10^{-6}$ at 60 Hz. The uncertainty in (10), the dielectric constant, may be as large as ± 10 percent even though the turns, n_{sd} and n_{dx} , are known to 1×10^{-6} . This is because the actual electrode spacing at low temperature is not known. In our measurements the room temperature value of d is used thereby assuming no thermal contraction of the sample. The thickness of these thin samples is not always uniform which also contributes to the error. Errors due to coating the sample with paraffin oil (discussed below) are negligible.

Similar considerations hold for the mandrel measurements. The real component of the dielectric constant is

$$\epsilon' = 0.113 n_{sd} n_{dx} C_S \ln Cr_2/r_1/L \quad (12)$$

where C_S is in picofarads and L is in meters.

The dissipation factor is the same as (11). Measurement errors are the same as for the parallel plate capacitor.

II. Dielectric Loss Results and Discussion

A. Parallel Plate Geometry

Many samples of different polymer tapes and epoxies were studied using the parallel plate apparatus described above. The polymers were all candidate insulators for the BNL flexible cable. The epoxies were either under consideration as spacers in the pipe-type cable being developed by the Linde Division of the Union Carbide Corporation (UCC-Linde) or were used as bushing material in BNL test apparatus. The sample holder was immersed in liquid helium at atmospheric pressure (4.2 K).

All samples were coated with paraffin oil prior to loading in the sample holder. Without the paraffin oil coating, the dissipation factor of all samples showed a strongly positive voltage dependence. This dependence could be greatly reduced by use of the paraffin oil, indicating the presence of voltage-dependent interfacial losses at the metal - plastic interface. These losses will be discussed more fully below. King and Thomas^[10] have shown that the paraffin oil coating introduces no additional contribution to the dissipation factor. They place the uncertainty of this determination at less than 1×10^{-6} at 60 Hz.

1. Polymer Tapes

The results of the polymer measurements are shown in Table I. The voltage dependence on $\tan \delta$ is in most cases quite small. Measurements were terminated at the first signs of partial discharge inception as

TABLE I. SUMMARY OF RESULTS AT 60 HZ AND 4.2 K

<u>Material*</u>	<u>Thickness</u>	<u>Maximum Voltage (Stress) Applied</u>	<u>Tan δ at Maximum Voltage</u>	<u>Tan δ at 200 V rms</u>
Polyamide (Nylon 11-A, non-oriented)	40 μ m	1000 V rms (25 kV/mm)	27×10^{-6}	24×10^{-6}
Polycarbonate-A (uniaxially oriented)	75	2000 (27)	69	61
Polyethylene-D (biaxially oriented, cross laminated)	100	2000 (20)	9	6.5
Polyethylene-B (biaxially oriented)	40	800 (20)	18	7
Polypropylene-C (non-oriented)	125	2000 (16)	7	3
Polypropylene-A (biaxially oriented)	30	1200 (40)	26	24
Polypropylene-B (biaxially oriented)	40	1200 (30)	15.5	17.5
Polysulfone-B (clear)	100	1000 (10)	100	96
Polysulfone-C (blue)	140	3000 (21)	126	113
Polysulfone-D (green)	140	1200 (9)	110	105
Polysulfone-E (green, fewer Na impurities)	110	1000 (9)	82	79
Polyether-sulfone-A (biaxially oriented)	10	400 (40)	28	62
Polyether-sulfone-B (non-oriented)	30	800 (27)	42	70

evidenced by unstable bridge behavior. The repeatability of polymeric samples from the same manufacturer is generally good although polymers with the same generic name may differ markedly. Several of the samples are seen to have $\tan \delta$'s less than 20×10^{-6} at design stresses of the order of 10 to 20 kV/mm. However, these materials have rather poor mechanical properties. The mechanically-sound materials have $\tan \delta$'s in the range of 50 to 100×10^{-6} . An attempt by the manufacturer to improve the $\tan \delta$ of one of these materials (green polysulfone) by reducing the sodium concentration met with some success.

The significant decrease in dissipation factor with increasing stress for the two polyether-sulfone samples is unique in our low-temperature experience. This negative voltage coefficient is a commonly observed property of power-factor capacitors and there the effect is well understood.^[11] The explanation for the observed behavior of polyether-sulfone remains unexplained.

As a check of our measurements one can compare our data with the published data of King and Thomas^[12] for experimental conditions of 4.2 K and 60 Hz. Agreement is excellent. The measurements are quite independent of each other since theirs rely on a temperature rise and ours on an electrical bridge balance to measure dissipation factor. Our measurements also agree rather well with those of Mopsik made at NBS.^[13] Mopsik's apparatus is capable of studying the low voltage behavior of small polymer samples as a function of temperature and frequency of applied voltage. Comparison of our data with his is not quite independent because the dissipation factor of his standard capacitor was supplied

by us. Nevertheless, we feel secure that this number is correct.

To examine the effects of paraffin oil on various interfaces, we studied several stacking arrangements of 30 μm -thick polypropylene films. This film was chosen because it exhibited a small voltage coefficient over a wide range of voltage stress. The dissipation factor of three-sheet stacks of this material was measured under the following conditions. In one case, both sides of each sheet were coated with paraffin oil. In another instance only the metal-insulator interfaces were coated. A two-sheet stack with oil only between the metal-insulator interfaces was also measured.

The results of these measurements are plotted in Fig. 11. The slopes are consistent with similar measurements made using the calorimetric method at another laboratory.^[13] Nevertheless, it is clear that the nature of the interfaces plays an important role in the dissipation factor of a composite structure at high stress. For this reason we decided that simulated cable insulation must be studied under conditions as close to those of the actual cable as possible. Hence, future studies of dissipation factor in composite structures were undertaken using the coaxial mandrel apparatus already described. The results of these measurements will be described below.

2. Epoxy Samples

Epoxy measurements offered an additional experimental difficulty as compared to polymer measurements: epoxy sheets must have surfaces which are parallel and free from imperfections. This is because epoxy, unlike

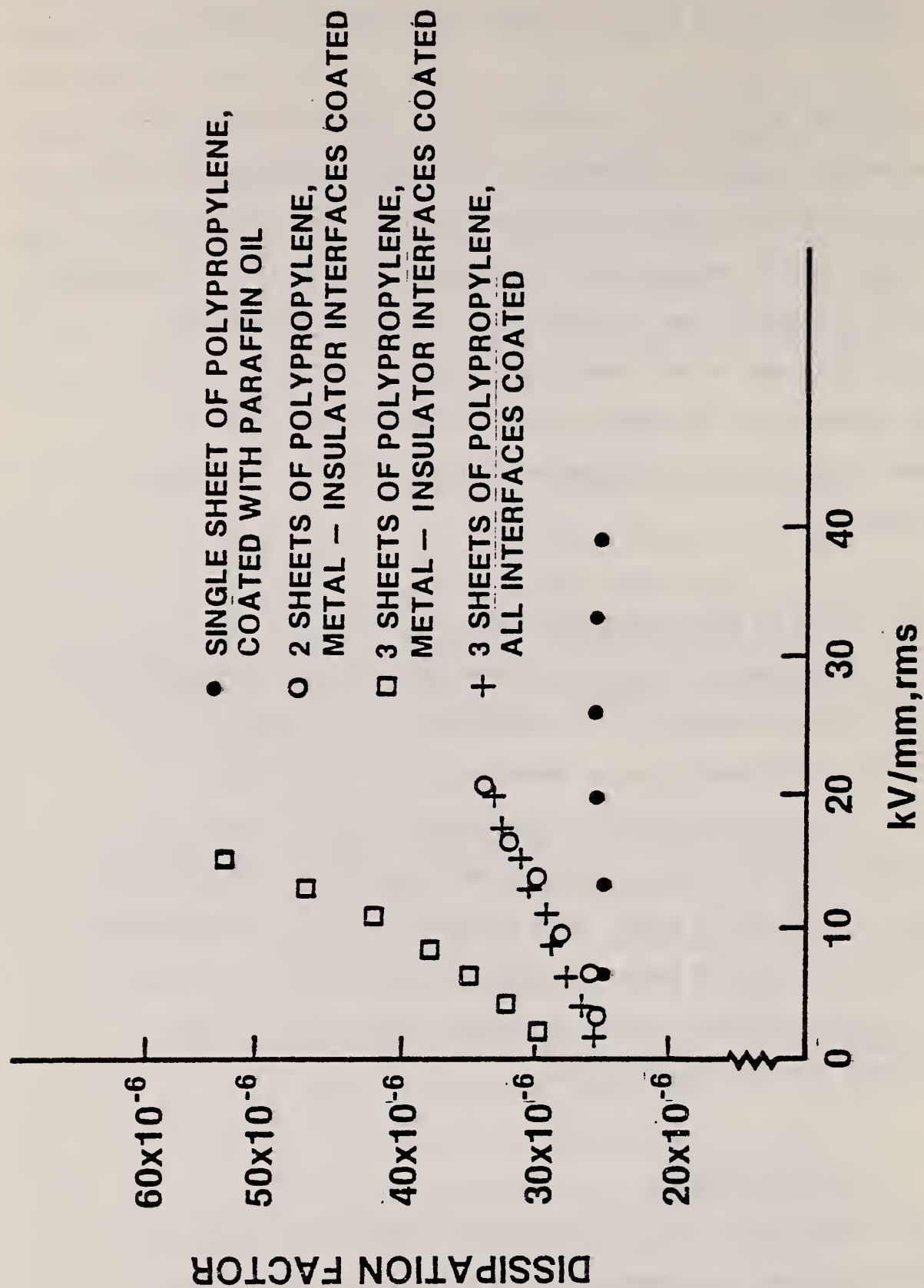


FIGURE 11 Multilayer stacks of polypropylene at 4.2 k, 1 atmosphere pressure.

plastic tapes, is not compliant at room temperature and thus will not seat well between the electrodes of the sample holder. Due to this problem, $\tan \delta$ measurements of epoxy samples which were not carefully fabricated exhibited a pronounced voltage dependence. In samples which were well-made, we observed a dependence of $\tan \delta$ with sample thickness. We were able to develop a theoretical model which explains the thickness dependence and allows us to ascertain the intrinsic D.F. of the material.

Our hypothesis to explain the observed thickness dependence of $\tan \delta$ is based on the following considerations. As a result of imperfect parallelism of the epoxy surfaces as well as the rigidity of epoxy at room temperature, the sample capacitance behaves as the model shown in Fig. 12. In addition to the epoxy, the capacitor dielectric includes a thin film of thickness τ and dielectric constant ϵ_1 . In our measurements this film is either mineral oil or liquid helium both of which have negligible loss. We assume τ is roughly the same for all well-made samples.

Assume the epoxy has a complex dielectric constant $\epsilon' + j\epsilon''$. Then the capacitance and dissipation factor of the epoxy-film composite may be found from the schematic representation of Fig. 12.

$$C_{EF} = A\epsilon'\epsilon_0 / \{d(1 + \epsilon'\tau/\epsilon_1 d)\}$$

$$(\tan \delta)_{EF} = (\epsilon''/\epsilon') / (1 + \epsilon'\tau/\epsilon_1 d) \quad (13)$$

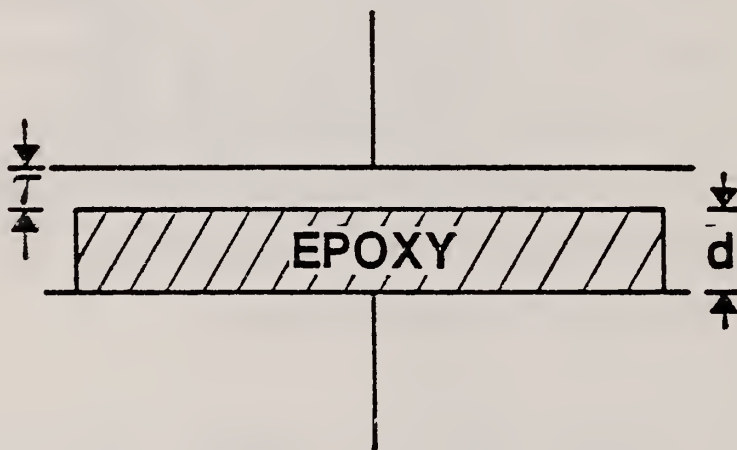


FIGURE 12 Model of epoxy behavior.

where A is the active electrode area, d is the sample thickness and ϵ_0 is the permittivity of free space. The model, therefore, predicts that the quantity $(\tan \delta)_{EF}/C_{EF}d$ is a constant which we shall call γ , and which depends only on properties of the epoxy.

$$\gamma \equiv \frac{(\tan \delta)_{EF}}{C_{EF}d} = \frac{\epsilon''}{A\epsilon_0\epsilon'^2} \quad (14)$$

Our hypothesis was tested with the aid of four samples of Perma-Rez CRS-48* differing in thickness but identical in composition. The samples were provided by UCC-Linde which took great care in their fabrication. Each sample was measured twice. The raw data are shown in Table II. The calculation of γ is carried out in Table III. The average value, γ , is equal to $11.94 \times 10^9 \text{ (F}\cdot\text{m)}^{-1}$ with a standard deviation of 1.6%. Thus, a prediction of the model has been verified.

Equation 13 may be rewritten in the form

$$(\tan \delta)_{EF}^{-1} = \epsilon'/\epsilon'' + \tau\epsilon'^2/\epsilon''\epsilon_1d. \quad (15)$$

A plot of $(\tan \delta)_{EF}^{-1}$ as a function of $1/d$ should give a straight line if our hypothesis is correct. Figure 13 shows this to be the case. The solid line was obtained using a least squares fit to the data. This fit gives a y-intercept of 2.55×10^3 and a slope of 0.3039 m. Then

TABLE II

Dissipation Factor Data of Epoxy Samples
 Tan δ was read directly from bridge,
 ϵ' was calculated from the thickness of the epoxy and
 the capacitance reading of bridge.

Perma-Rez CRS-48*, 60 Hz, 4.2 K

1020 μm thick sample

<u>Voltage</u> (volts-rms)	<u>tan δ</u> <u>Run #1 ($\epsilon' = 3.14$)</u>	<u>tan δ</u> <u>Run #2 ($\epsilon' = 3.22$)</u>
100	348×10^{-6}	354×10^{-6}
200	347	353
400	344	
600	340	
800	337	
1000	335	
2000	335	

510 μm thick sample

<u>Voltage</u>	<u>tan δ</u> <u>Run #1 ($\epsilon' = 2.86$)</u>	<u>tan δ</u> <u>Run #2 ($\epsilon' = 3.08$)</u>
100	314×10^{-6}	335×10^{-6}
200	312	333
400	303	
600	297	
800	289	
1000	283	
1500	270	

249 μm thick sample

<u>Voltage</u>	<u>tan δ</u> <u>Run #1 ($\epsilon' = 2.24$)</u>	<u>tan δ</u> <u>Run #2 ($\epsilon' = 2.38$)</u>
100	252×10^{-6}	265×10^{-6}
200	249	260
400	247	
600	244	
800	245	
1000	251	

140 μm thick sample

<u>Voltage</u>	<u>tan δ</u> <u>Run #1 ($\epsilon' = 1.96$)</u>	<u>tan δ</u> <u>Run #2 ($\epsilon' = 1.88$)</u>
100	223×10^{-6}	204×10^{-6}
200	219	200
400	217	
600	225	

TABLE III

Calculation of Model Constant, γ

d(m)	D.F.	C(F)	$\gamma \frac{1}{F \cdot m}$
1.016×10^{-3}	348×10^{-6}	28.6×10^{-12}	11.98×10^9
1.016×10^{-3}	354	29.3	11.89
0.508×10^{-3}	314	52.1	11.86
0.508×10^{-3}	335	56.2	11.73
0.249×10^{-3}	252	83.5	12.12
0.249×10^{-3}	265	88.7	12.00
0.140×10^{-3}	223	129.8	12.27
0.140×10^{-3}	204	124.5	<u>11.70</u>

AVE = 11.94×10^9

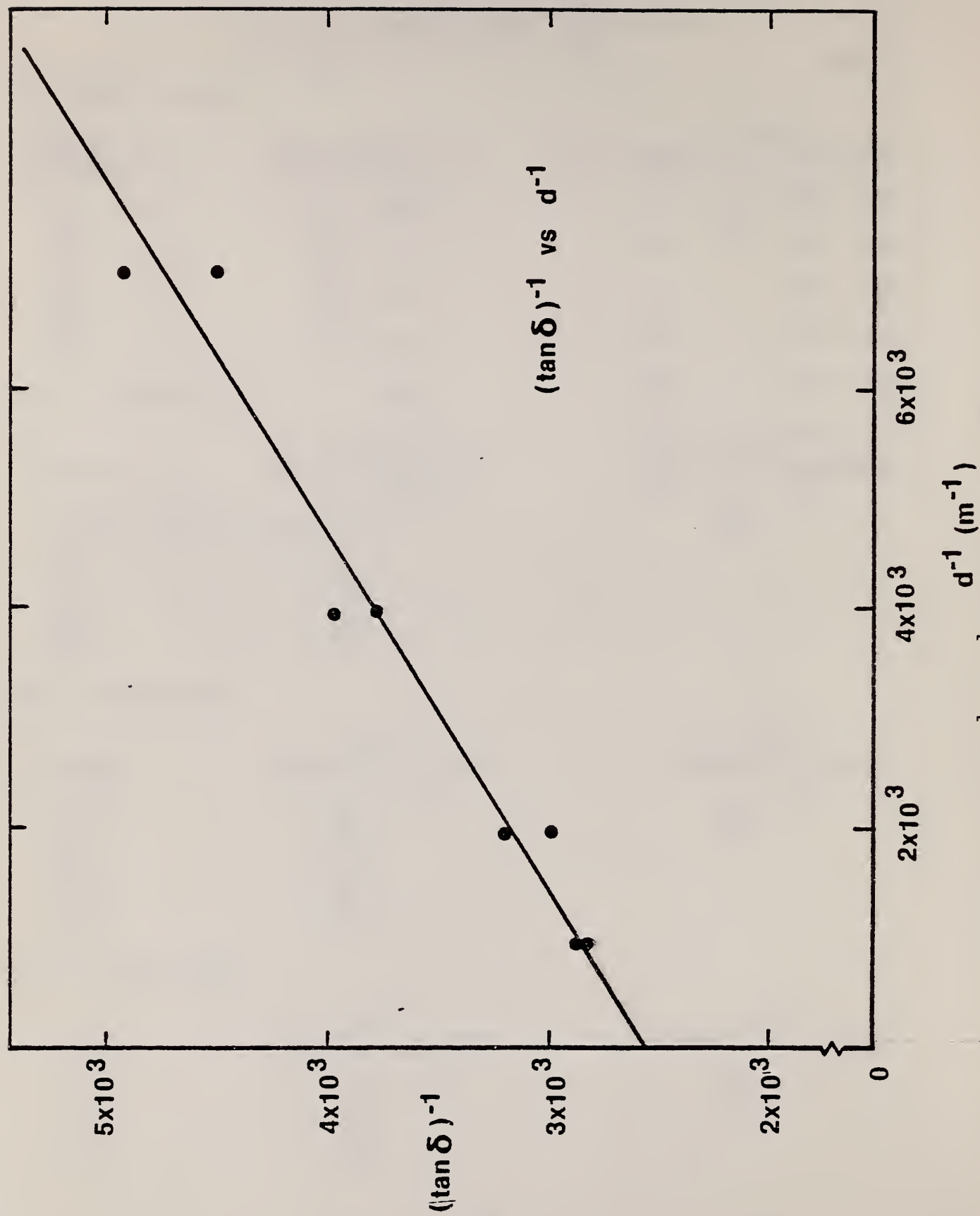


FIGURE 13 $(\tan \delta)^{-1}$ vs d^{-1} for epoxy measurements.

$$\tan \delta = \epsilon''/\epsilon' = 392 \times 10^{-6} \text{ and}$$

$$\epsilon' = 3.53.$$

The one adjustable parameter in our model, γ/ϵ_1 , is found to have a value of 3.37×10^{-5} m. Since the dielectric constant of the helium or mineral oil film is about 1 or 2, τ , the thickness of the film is predicted to be about 20 μ m. This number cannot be verified but it seems reasonable to us since it is the same order as machining tolerances.

Evidently, epoxy sample results must be interpreted with considerable care in order to avoid error. Measurements on a single, thin sample must be viewed with dubiety. Further, different lots of epoxy may have dissipation factors which depend on the details of preparation. We have measured various epoxies used in the casting of high voltage bushings and find their dissipation factors to vary over a range of $(200 - 350) \times 10^{-6}$ depending on the lot. We have also measured a 1.6 mm-thick sample of G-10, a material commonly used as circuit board and found its $\tan \delta$ to be 560×10^{-6} and its dielectric constant to be 4.2.

B. Coaxial Geometry

The tests using the parallel-plate electrodes were designed to obtain data on the intrinsic behavior of various materials under consideration as insulation in superconducting cables. The mandrel measurements were designed to study the behavior of the composite insulation being considered for the BNL cable. This insulation composite consists of layers of plastic tape wound at a particular registration (we used a 65-35 registration for all our measurements) and the helium which fills the butt gaps formed by the plastic tape layers. This is analogous to conventional, flexible oil-filled cable but, instead of kraft paper and oil, one uses plastic tapes and helium. Of particular concern at high electrical stress is the butt gap region. It is here that field enhancement will occur, caused by the dielectric mismatch between helium ($\epsilon' \sim 1.0$) and plastic ($\epsilon' \sim 2$). In an effort to improve the breakdown properties of the helium-filled butt gaps, the cable is operated at high pressure. At design conditions, the helium is in a region past its triple-point. In this "supercritical" region the formation of bubbles is suppressed because a gas-liquid interface cannot exist under equilibrium conditions. The suppression of bubble formation improves the breakdown properties of the helium. In addition, the heat capacity of the helium is a maximum along the transposed critical line^[14] which is useful to the engineering of the cable refrigeration.

The first measurements made were with a simple composite structure: four layers of 75 μm - thick Valeron* wound directly on the bare mandrel. Copper was wrapped around the Valeron* in order to form a three-electrode, guarded coaxial capacitor as described above.

The sample was immersed in helium and the dissipation factor was measured at a range of helium pressures (170 kPa to 1,150 kPa). The temperature was varied from 8 K to 9.5 K. Typical data are shown in Fig. 14. As with all the data obtained from this sample, the dissipation factor begins at a value less than 10^{-5} , increases very gradually with applied stress and then at a well-defined, reproducible point begins to increase rapidly with electrical stress. The "break point", or point at which the D.F. becomes strongly dependent on electrical stress, is a function of the density of helium in the butt gaps. Pertinent numbers are gathered in Table IV.

The variability in D.F. measurements before the break point as a function of different helium densities has a range of less than 2×10^{-6} . The tendency for D.F. to be somewhat lower at higher He density may be due to experimental scatter but might also be caused by the disappearance of interfacial losses at higher helium densities. The observed effect is too small to permit one to be certain of its origin.

The observed function of break point stress with helium density, when normalized to the maximum stress, is identical to Meats' results for the breakdown of supercritical helium.^[15] The correlation of our break point data with Meats' helium breakdown data suggests strongly that the break point signals the start of discharges in the butt gaps. We were not able to correlate the numerical values of break point stress with Meats' data because of the geometrical complexity of a practical cable sample.

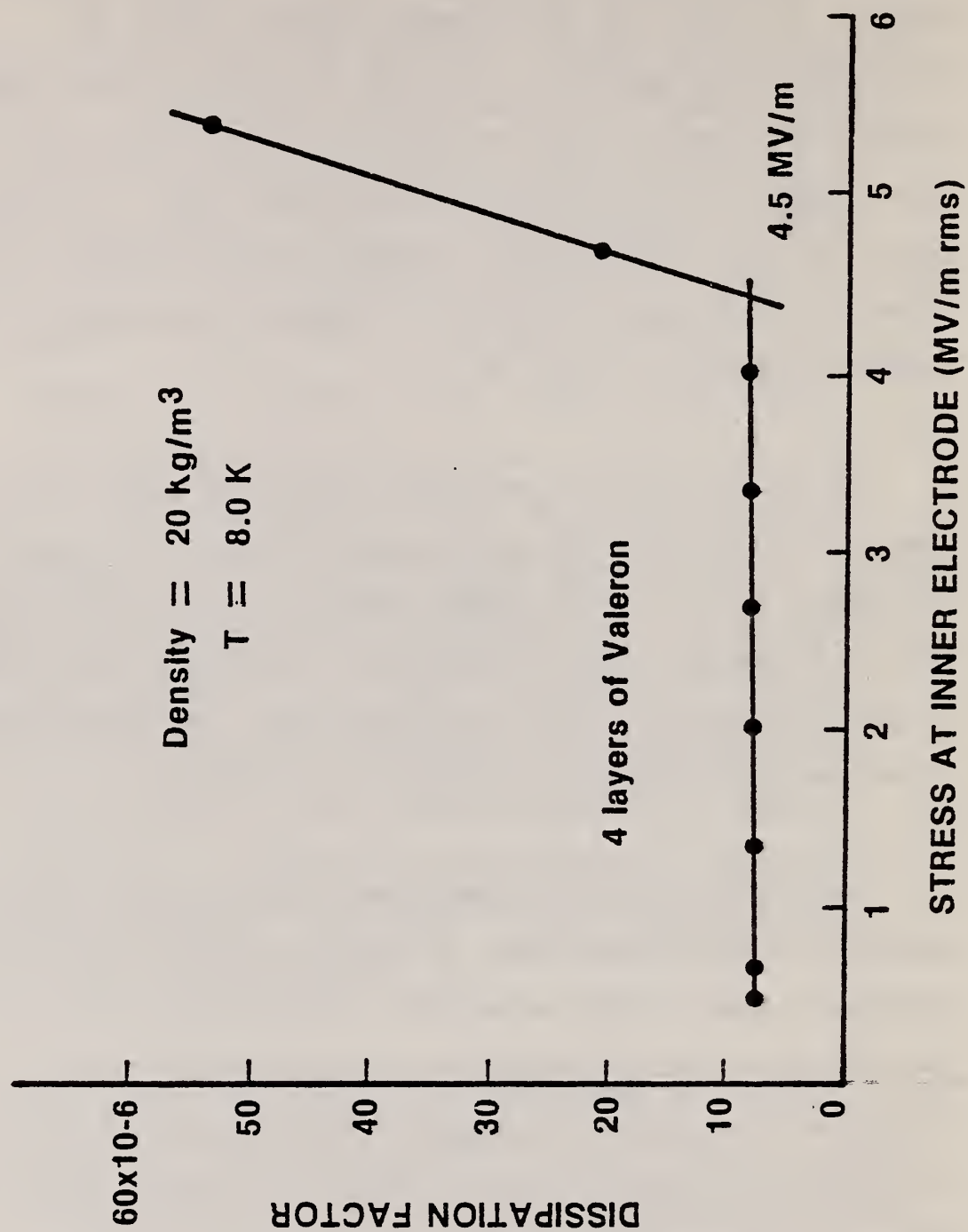


FIGURE 14 D.F. of Valeron* in coaxial geometry.

TABLE IV

Dissipation Factor Results of Valeron* Samples in Coaxial Geometry

<u>He Density</u>	<u>Temperature</u>	<u>D.F. at 1MV/m (inner electrode)</u>	<u>Stress at Inner Electrode at "Break Point"</u>
9 kg/m ³	9.3 K	8.2×10^{-6}	3.2 MV/m
20	8.4	8.4	4.5
45	8.5	7.4	7.2
70	8.7	6.4	12.5
90	8.9	7.3	11.1

It was also observed by using a commercial partial discharge detector that the break point corresponds to the partial discharge inception voltage. The sensitivity of the partial discharge detector was ~ 0.2 pC. If the increase in D.F. is due to discharges of magnitude q at a single site, then elementary considerations^[16] predict that the dissipation factor caused by these discharges is

$$\text{D.F.} = \sqrt{2} q / \pi C V$$

where C is the sample capacitance and V is the applied rms voltage. In the case of the sample under study, $C \simeq 950$ pF. Since the resolution of our capacitance bridge is $\pm 0.2 \times 10^{-6}$ in D.F., repetitive discharges of order ~ 1 pC can be detected at an applied voltage of 1 kV. (This voltage corresponds for the sample under study, to a stress of 3.4 MV/m at the inner electrode).

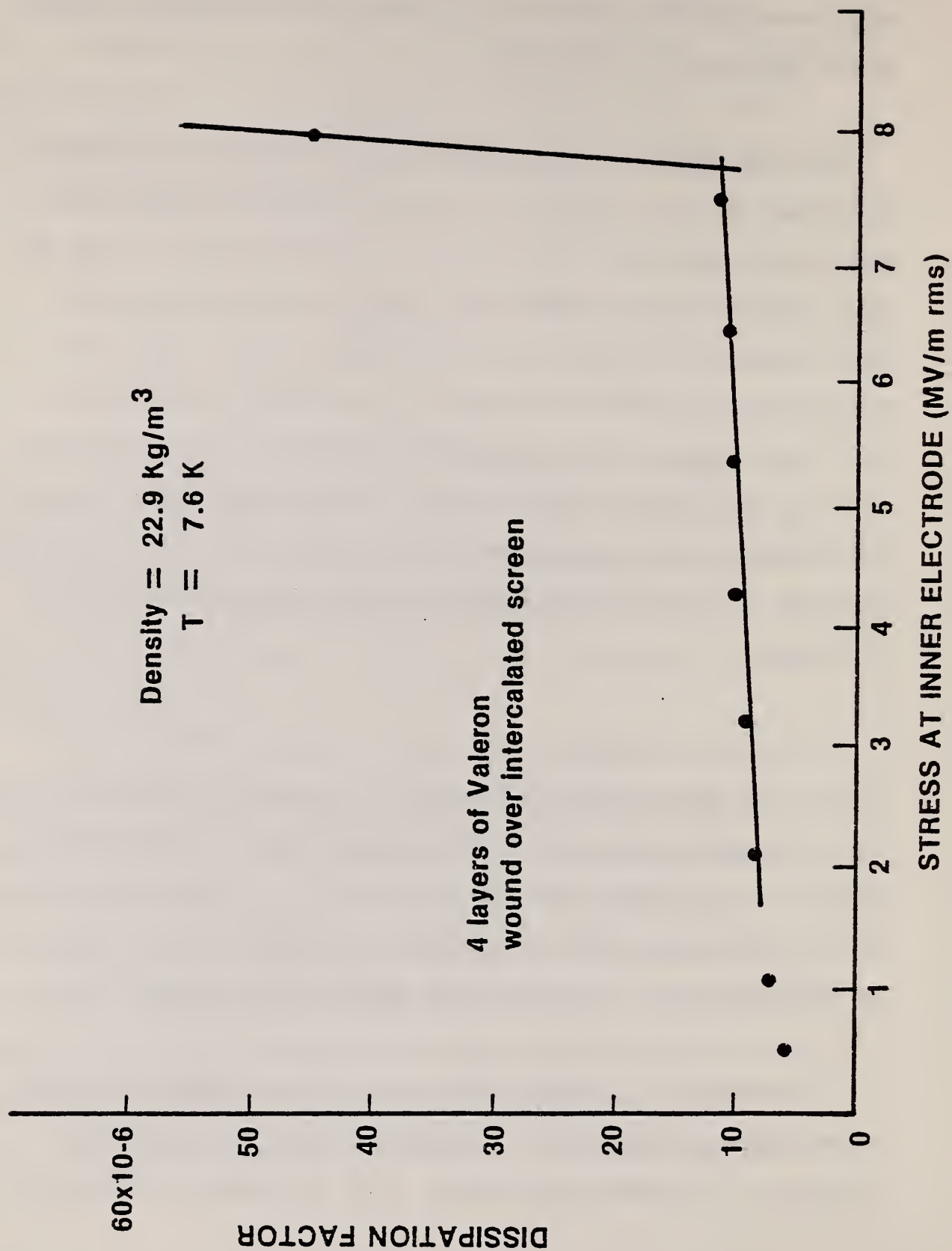
Partial discharges were detected using a commercially available, balanced detector. Balanced detection was used to suppress the effect of voltage pulses which may occur at the output of the power supply. These unwanted discharges were further suppressed by the presence of a 100 k Ω resistor between the power supply and the sample. This resistor and the stray capacitance to ground on the load side of the resistor form an effective low-pass filter. The resistor also limits current in the event of a flashover or breakdown at the sample. The high voltage wiring

was identical for the measurement of D.F. and for corona detection. Only low-voltage leads needed to be changed in order to proceed from one type of measurement to the other.

Once the behavior of this simple system was studied and reliably reproduced, the next step was to see how the addition of bedding and screen layers would alter the behavior. It was anticipated that the BNL cable insulation would be wound over a spongy semiconducting bedding layer covered by an intercalated layer of plastic tape. The plastic tape would have one metallized surface (at the bedding interface) and would thus serve as a screen. Polytetrafluoroethylene impregnated with carbon was the choice of bedding layer. The bedding was deemed necessary for mechanical reasons and, of course, the screen would then be necessary to prevent ac losses which the semiconducting bedding would otherwise introduce.

We first ran a sample of four layers of Valeron* wound over an intercalated layer of metallized Valeron*. The results were similar to the system without the screen. The screen did cause a slight slope to appear in the pre-break point section of the D.F. vs. stress curve (Fig. 15) but the break point itself now occurred at a somewhat higher stress. No additional partial discharges were observed below the break point.

Introduction of a bedding layer could not be studied carefully due to more immediate needs of BNL for measurements on a new candidate insulation. Preliminary measurements (Fig. 16), however, indicated that introduction



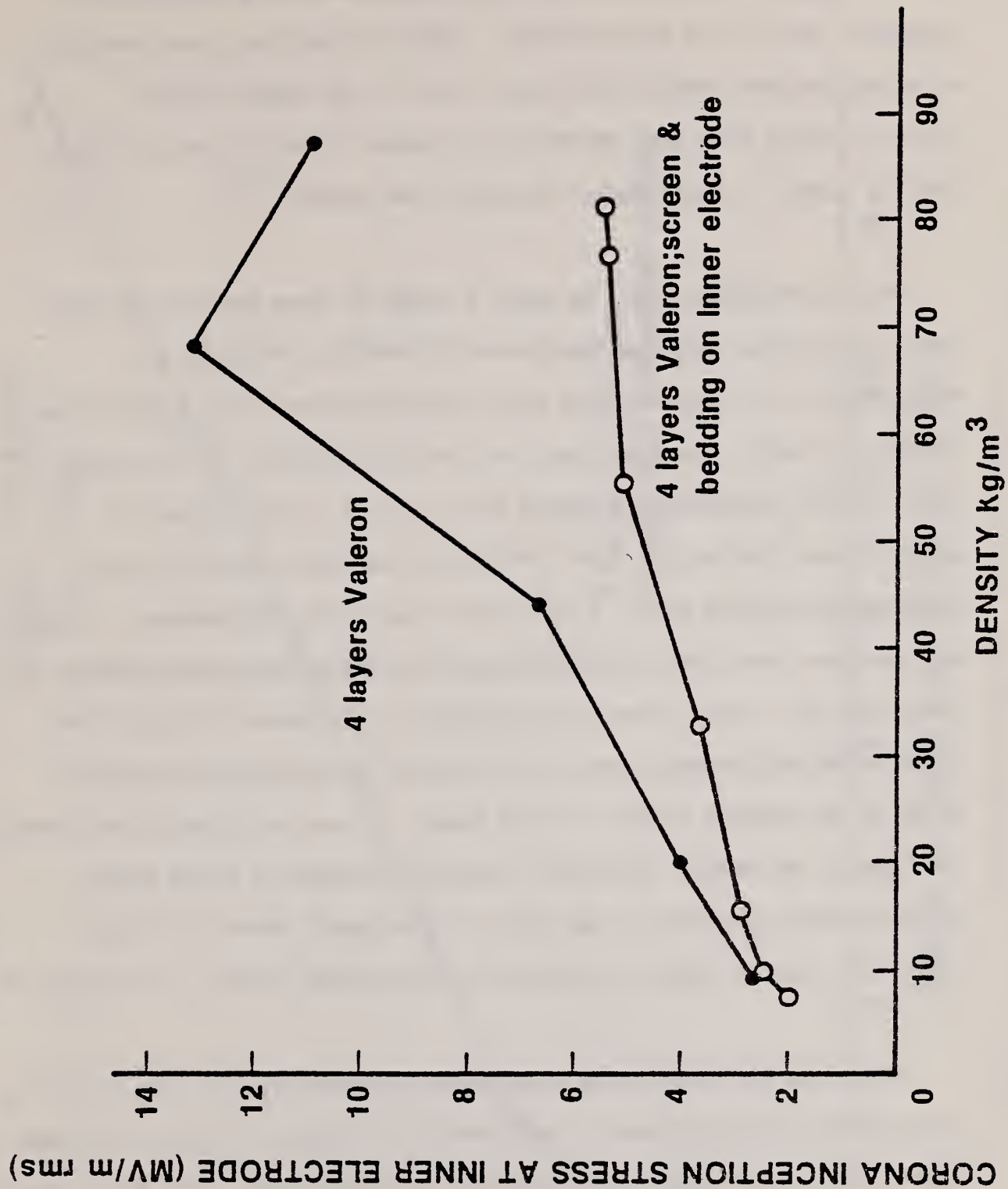


FIGURE 16 Corona inception stress of Valeron* sample in coaxial geometry with and without screen and bedding layers.

of a bedding layer between the bare electrode and the screen greatly increased the D.F. of the composite. Partial discharges were detected at voltage minima indicating contact noise in the sample holder. Similar results have been observed by a General Electric group studying bedding layers in experimental cryoresistive cables.^[17]

At the request of BNL, we began a study of three composite polymer tapes. The tapes have been designated PP-U-PP(B), 3PP-2U(A) and PP-PE-PP(B). All three were 19 mm in width and were color-coded (blue, violet, and red). The blue tape (PP-U-PP(B)) consisted of two layers of 32 μm - thick polypropylene bonded with a 2.5 μm - thick layer of polyurethane. The violet tape (3PP-2U(A)) had three layers of the polypropylene bonded with 2.5 μm - thick layers of polyurethane. Finally, the red tape (PP-PE-PP(B)) had two layers of the polypropylene bonded with a 2.5 μm - thick layer of polyethylene. Microscopic study of the tapes by the NBS polymers group had revealed the presence of numerous voids in the bonding layers of these tapes. It was anticipated that measurement of the D.F. and partial discharge inception voltages of these tapes would elucidate the role of the voids in the tapes' behavior at high electrical stress. Some of the results are plotted in Figs. 17 through 19.

While the different tapes show different behavior, the results are such as not to be explained by consideration of voids in the polyurethane binding layer. Such consideration would predict the violet tape, with the highest percentage of binding layer, would have the greatest loss. A comparison of the data for the three laminated samples shows that the violet sample (3PP-2U(A)) has somewhat superior dissipation factor properties at the high electrical stresses of interest. The violet

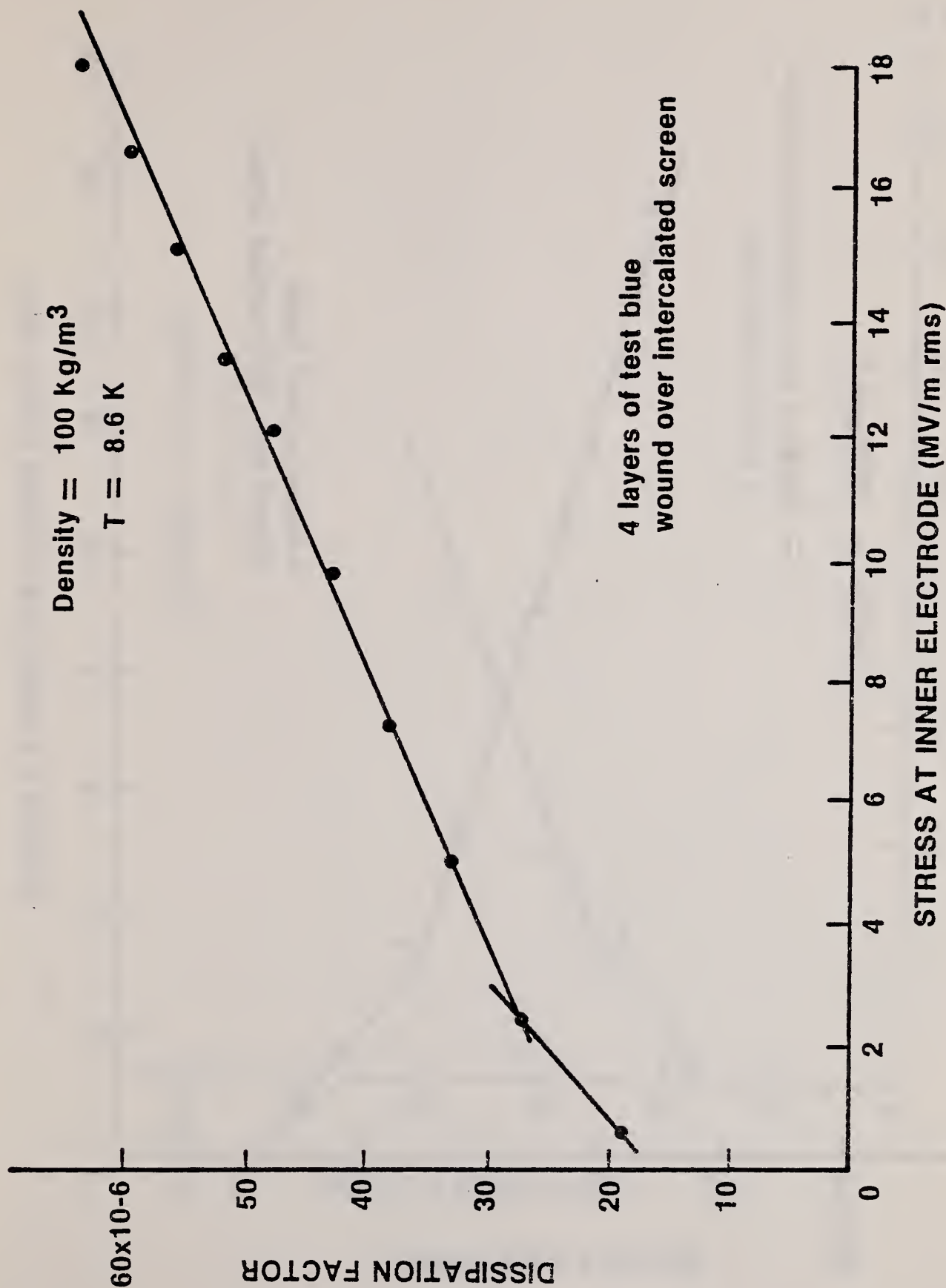


FIGURE 17 D.F. of PP-U-PP(B) sample in coaxial geometry.

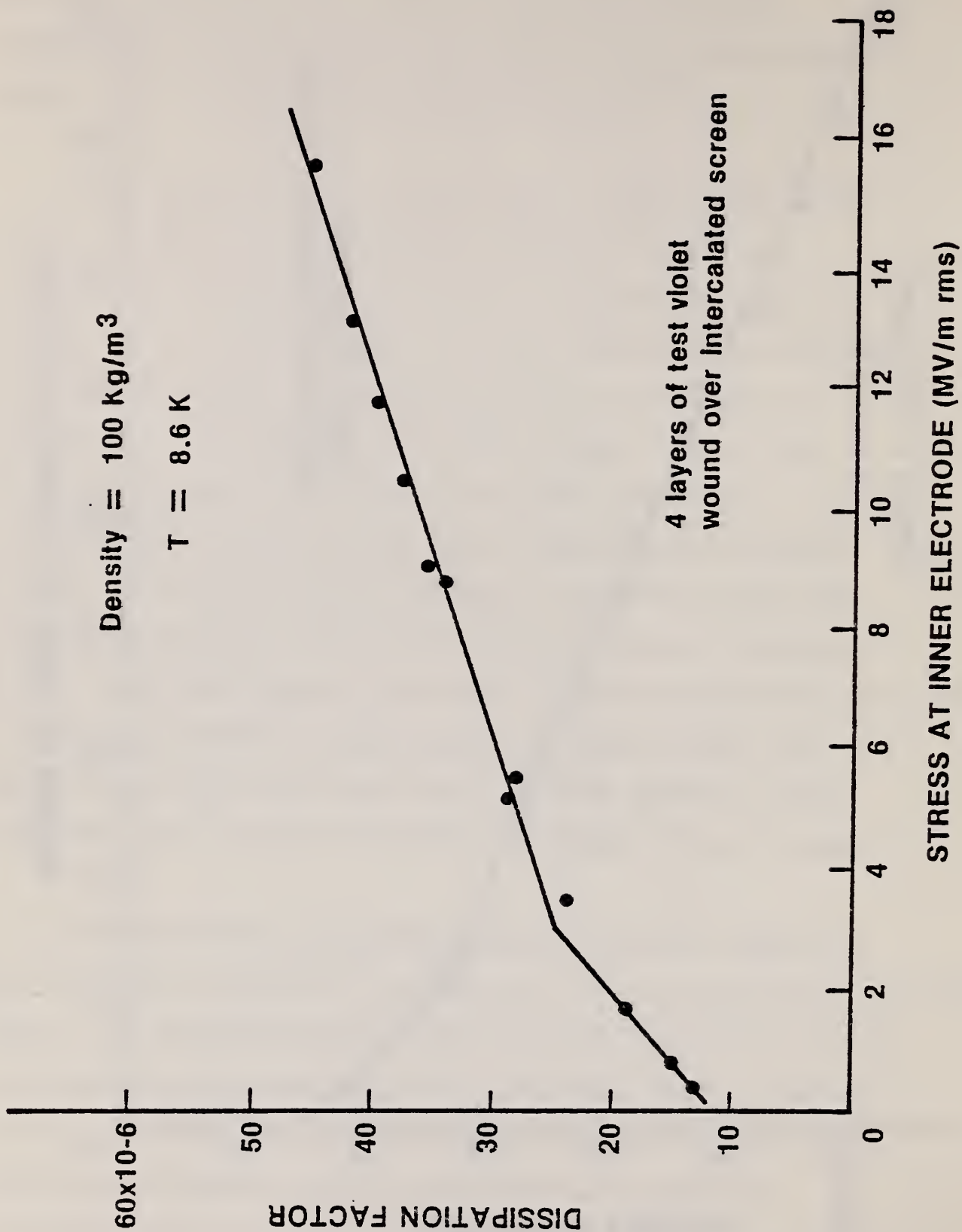


FIGURE 18 D.F. of 3PP-2U(A) sample in coaxial geometry.

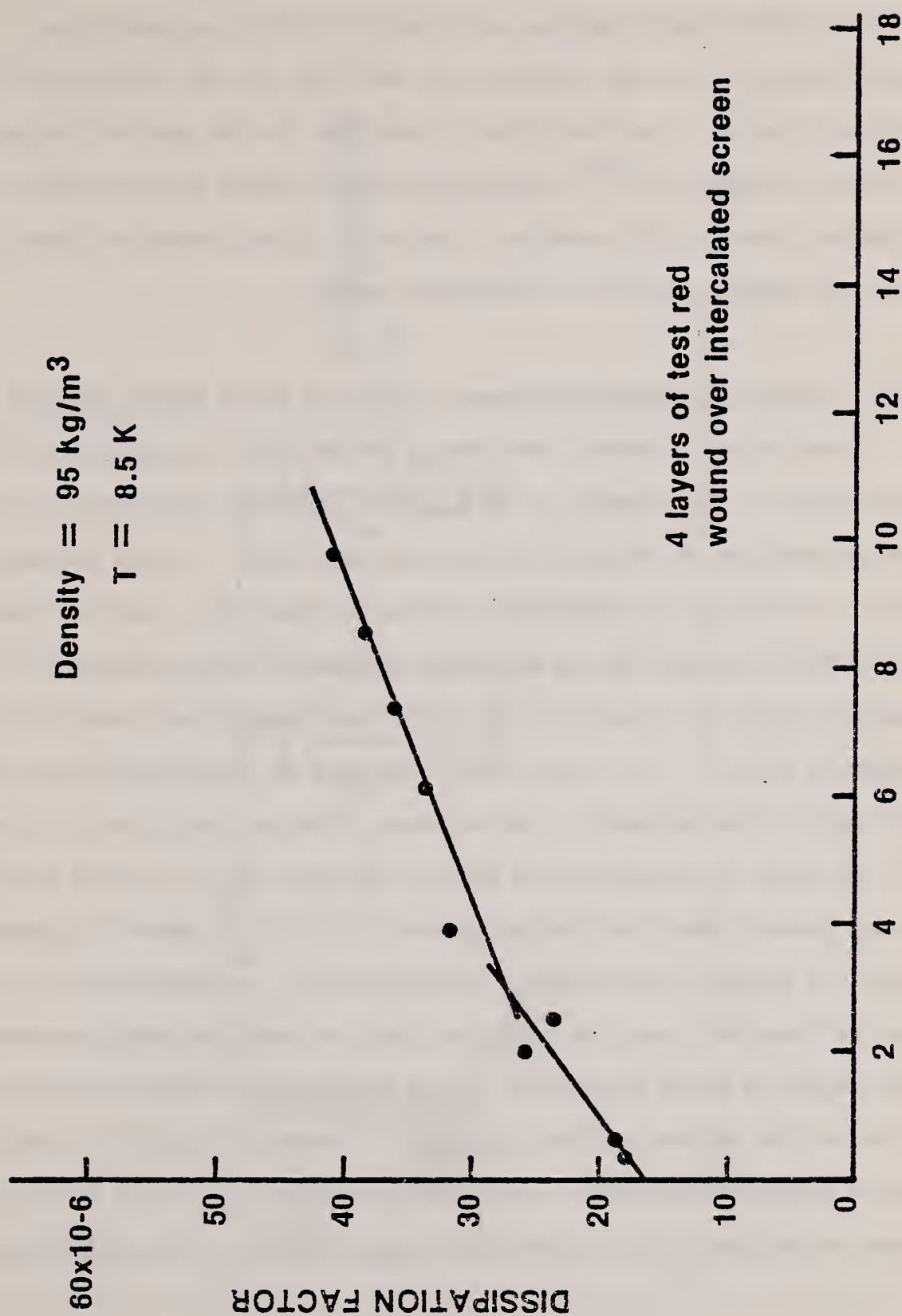


FIGURE 19 D.F. of PP-PE-PP(B) sample in coaxial geometry.

sample and the blue sample both have relatively thin polyurethane layers but the violet sample has two such layers with four polypropylene-polyurethane interfaces compared with one layer and two interfaces for the blue sample. The discussion by Khoury in the BNL quarterly report dated 2 November 1977^[18] on the morphology of these two tapes does not give any clues to this behavior. The voids in the laminating layers of the two tapes are similar in shape and number.

III. Partial Discharge Measurements Using the Pulse Height Analysis System

The partial discharge measurement system (PDMS) as developed at NBS (described in the appendix to this report) performs high-speed pulse-height-analysis of the partial discharge amplitudes. It can be used much the same way as conventional discharge detectors. That is, the PDMS may be attached to the detection impedance of any conventional partial discharge circuitry.^[19] The circuit used in our laboratory is shown in Fig. 20. It is very nearly the same as the bridge circuit used for our D.F. measurements. The resistor, R , which limits supply current in the event of breakdown also forms a low-pass filter with the stray capacitance between the load and ground. This filter tends to suppress spurious spikes in the supply. The capacitor C_k is conventionally known as the "coupling capacitor". In our case, we used the same compressed-gas capacitor which also served as our standard for bridge measurements. The low side of the coupling capacitor is connected directly to ground as is its guard electrode. The sample capacitor, C_x , is, of course, the same as was used in our mandrel measurements of D.F. The guard electrodes

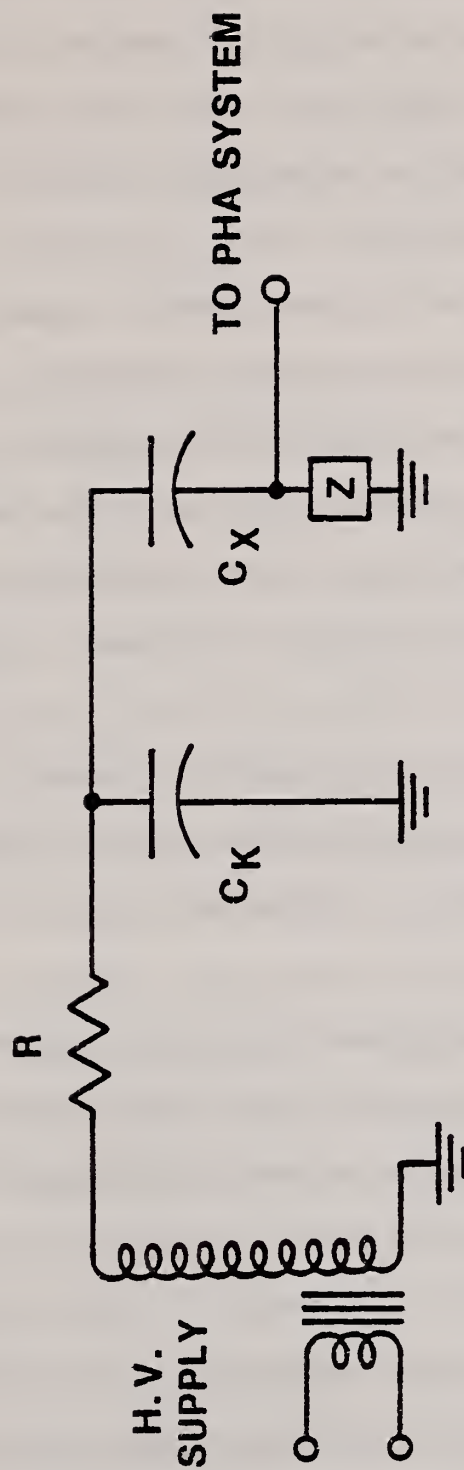


FIGURE 20 High-voltage circuit for partial discharge measurements.

of C_x are connected to ground while the low voltage electrode is connected to the detection impedance, Z . In our case, Z consisted of a resistor, capacitor and inductor in parallel. The RLC circuit parameters were chosen so that a very narrow pulse (≤ 30 ns) produces an output of a critically damped pulse of width ~ 2 μ s. Of course, the choice of capacitance in the RLC circuit is not entirely discretionary because of unavoidable strays in parallel with R and L . It should also be noted that the guard capacitances of the three-terminal capacitors C_k and C_x act in parallel to effectively increase the value of C_k . This is an important consideration if the signals on the detection impedance are to be related theoretically to partial discharges in the sample. The actual calibration of the entire system was carried out experimentally at low voltage by using a pulse generator in conventional fashion.^[18]

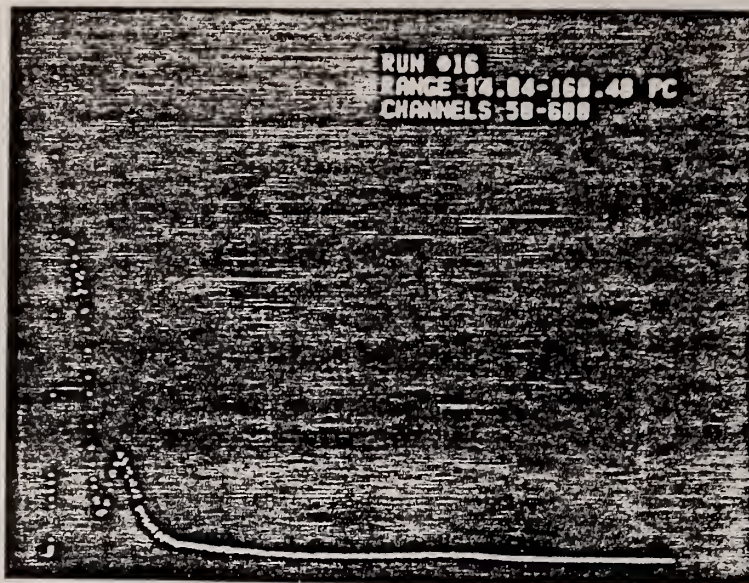
Time and other constraints only permitted the use of the PHA system in one actual test. This was an attempt to monitor a sample of cable insulation under consideration of accelerated aging.

The partial discharge measurement system is a powerful tool for studying the aging of cryogenic dielectrics under discharge conditions. In order to design a meaningful experiment, some mechanism must be provided to accelerate this aging process so that some changes might be observed during the course of the experiment. Accelerated aging might be accomplished by increasing the frequency of the alternating voltage, raising the sample temperature or some other means. An attempt was made to accelerate the dielectric aging by running at high stresses so that large discharge activity was observed (discharges of the order of 200-300 pC).

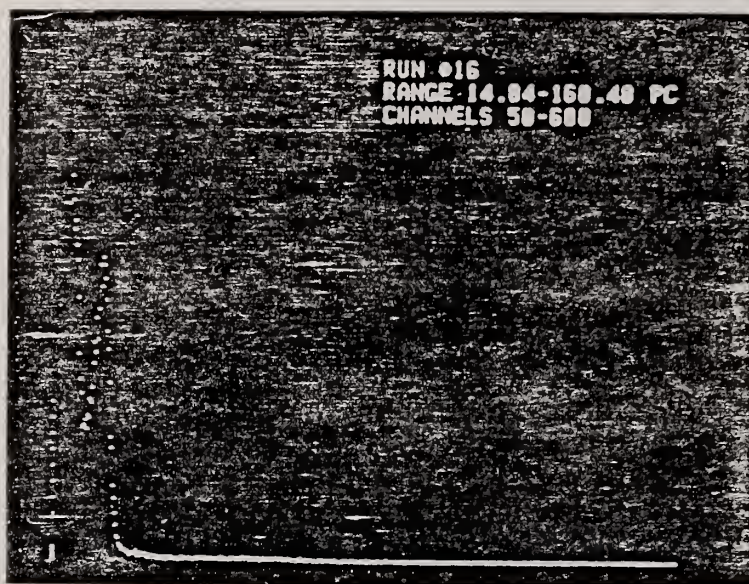
The sample measured consisted of four layers of Valeron* wound over two intercalated tapes of metalized Valeron*. There was no bedding layer. The sample was run at a pressure of about 1.35 megapascals and a temperature of about 8 K. The applied voltage was 6.95 kV which is equivalent to an electrical stress of about 18 MV/m. The partial discharge inception level for this sample was at about half this stress.

The original plan was to run this sample at this elevated stress for as long as liquid remained in our cryostat (~ 15 hours). The pulse height distributions at the beginning of the run, two hours later, and 3-1/2 hours into the run are shown in Fig. 21. These are not cumulative distributions but are fresh distributions taken for a 10 minute interval at the measurement time. While there appear to be some differences (the valley disappears with time), the distribution of large discharges does not vary significantly. About a half hour after the last picture in Fig. 21 was taken, our partial discharge measurement system suddenly stopped working. An analysis of the hardware indicated that a protection diode in a preamplifier failed. After removing this preamplifier and the partial discharge measurement system, the sample was reenergized and discharges monitored with a conventional discharge detector. The sample appeared to be normal suggesting that the failure was unrelated to the sample.

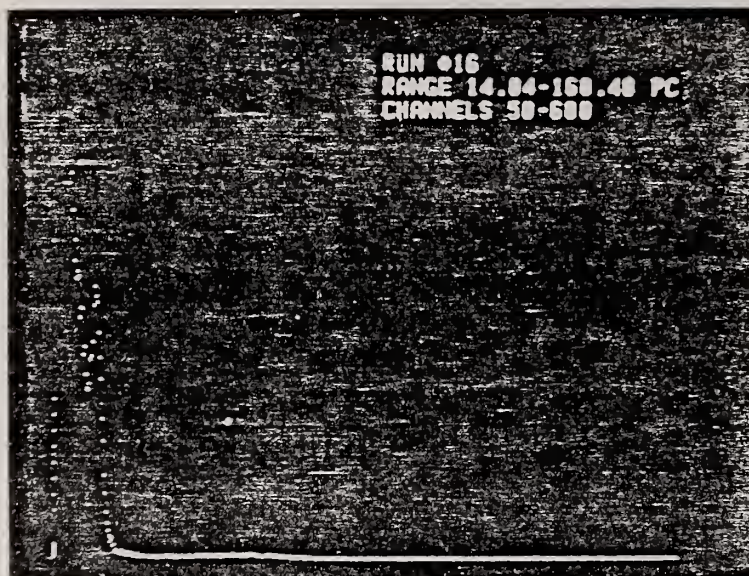
It was decided to repeat the same test using the same sample with improved preamplifier protection. Figures 22a and b show the results at the beginning of the test and 2-1/2 hours later. The results are similar to the first test on this sample except that the valley has disappeared.



(a) Beginning

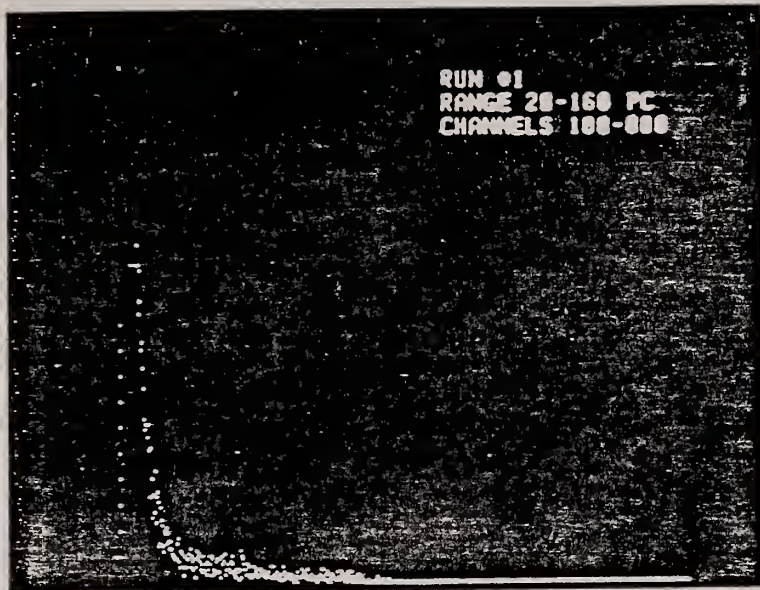


(b) 2 hours later

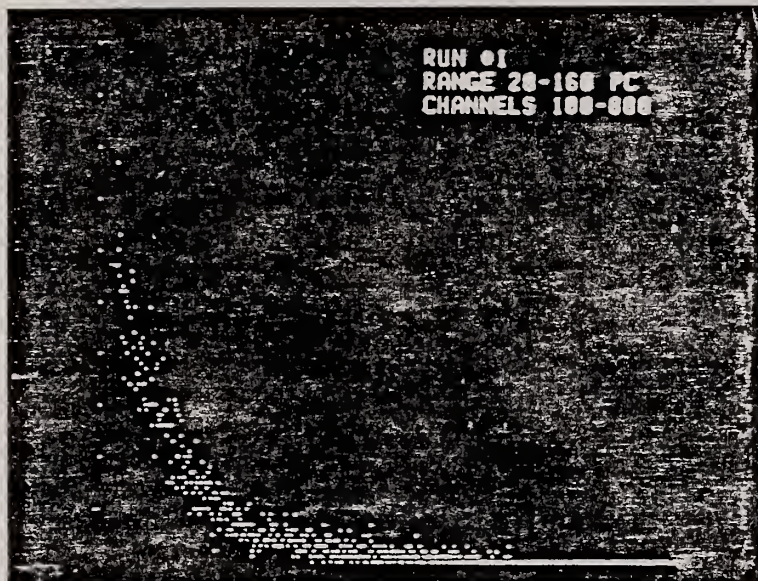


(c) 3 1/2 hours later

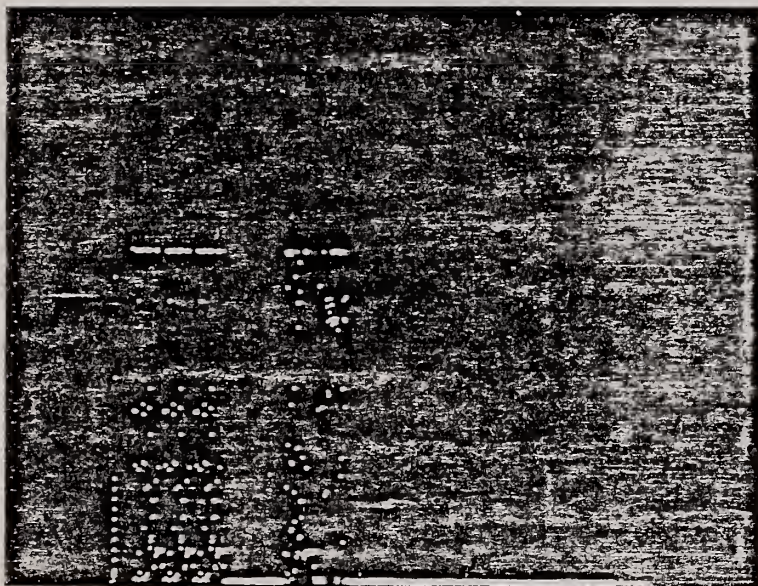
FIGURE 21 Discharge spectra-first run.



(a) Beginning



(b) 2 1/2 hours later



(c) After failure

FIGURE 22 Discharge spectra-second run.

Between the two runs the problem of the dynamic range of the system, mentioned in the Appendix, was readdressed. It now appears likely that the valley in the distribution observed in the first run was a result of improper setting of the threshold detector caused by an erroneous value for the dynamic range. It appears that the sample in the second run has changed little after almost 3 hours at 18 MV/m. At the three hour point the sample failed. This time, with improved protection for the preamplifier, the system survived and the discharges indicating failure were observed on both the conventional corona detector and the pulse-height analysis system. Figure 22c shows the output of the latter system. The discharge rate was so large that the minicomputer was "locked up" and had to be shut off and "rebooted" to retrieve the data. Figure 22c shows that several of the channels are filled (32,767 counts). The fact that certain channels are filled and others appear empty probably is not significant. At high discharge rates the a-d converter and related logic could not perform accurate conversions.

The voltage was reduced to zero and the inception voltage for this failure was measured. As opposed to the first run on the sample, this time the inception voltage was practically at the turn-on voltage indicating permanent damage to the sample. After the sample had reached room temperature, it was measured again with SF_6 . The inception voltage was still very low.

There was a striking similarity between the failures for the two runs (or possible failure for the first run). They both occurred about the same time after the run began. It was first thought that this meant the dielectric tapes were aging in the presence of this high stress. But now the significant similarity appears to be that the liquid helium in the dewar had reached the identical level at the time of the two failures, 63 cm from the bottom of the helium dewar. Since this is near the bottom of the pressure vessel, it is likely that the temperature differential along the mandrel length is increasing at this point. While a 2 K temperature differential is often observed, an increase to 4 K would decrease the helium density at the top of the mandrel to about half the value at the bottom.

When the mandrel was removed from the pressure vessel, a puncture was observed through the four layers of Valeron* and the intercalated screen. The site of the puncture was under a relatively sharp corner edge of the guard electrode at the very top of the sample.

Termination of this project prevented us from continuing these measurements in order to systematically study aging processes at cryogenic temperatures. The partial discharge measurement system has proven most valuable in other measurements such as the study of partial discharge behavior in sulfur hexafluoride.

APPENDIX

Partial Discharge Measurement System

A partial discharge measurement system (PDMS) was developed in order to study aging processes in electrical insulation. While the original system was designed for the studies of partial discharge behavior at cryogenic temperatures, the PDMS has been used for more conventional insulation systems as well. The PDMS uses the technique of pulse-height-analysis in order to obtain amplitude spectra of the partial discharges as a function of time. Changes in these spectra as a function of applied electrical stress, frequency, temperature, pressure, impurity or defect concentration could yield important information on aging processes.

Pulse-height-analysis has been used to study partial discharges previously.^[A-1] The system developed at NBS has the advantage of being significantly faster (i.e., the dead time is only 8 μ s compared to about 50 μ s for conventional systems). The key to this speed is a fast analog-to-digital converter and the use of the direct-memory-access input to a minicomputer used for data acquisition. Having a minicomputer as part of the system results in increased power and versatility compared to other systems based on conventional multichannel analyzers.

A description of the PDMS will be presented in two sections: hardware and software. The intent is to provide enough information so that the system could be duplicated by others if they wished.

I. Hardware

A. Detection Impedance and Amplifier

A typical detection impedance, Z , is shown in Fig. A-1. Typically the impedance is some RLC circuit tuned for optimum system behavior. The selection of this impedance can affect the dynamic range of the PDMS. If a discharge results in an under-damped oscillation, the PDMS can be adjusted so as not to trigger on the subsequent peaks. This, however, increases the dead time. This detection impedance also severely limits protection devices that can be used. Normally some protection should be placed between the detection impedance and the amplifiers to follow. Unfortunately high-speed protection devices have too large a capacitance resulting in very small signal levels and far from critically damped performance. Care must therefore be taken in circuit design so that if a breakdown does occur the most likely component to fail will be readily replaceable.

A small but significant level of 60-Hz voltage (and harmonics) is present at the detection impedance. This voltage, becoming more serious at higher voltage levels, can cause the peak-and-hold circuitry to trigger on the peaks of the applied sinusoidal voltage giving erroneous discharge spectra and ultimately saturating the lower channels.

A standard method of reducing this voltage is to use balanced detection of the partial discharge pulses. The balance is made to null the common-mode partial discharges which may be occurring in the power supply, for example, but this balance is generally close enough to a 60 Hz balance to eliminate this source of voltage. Balanced

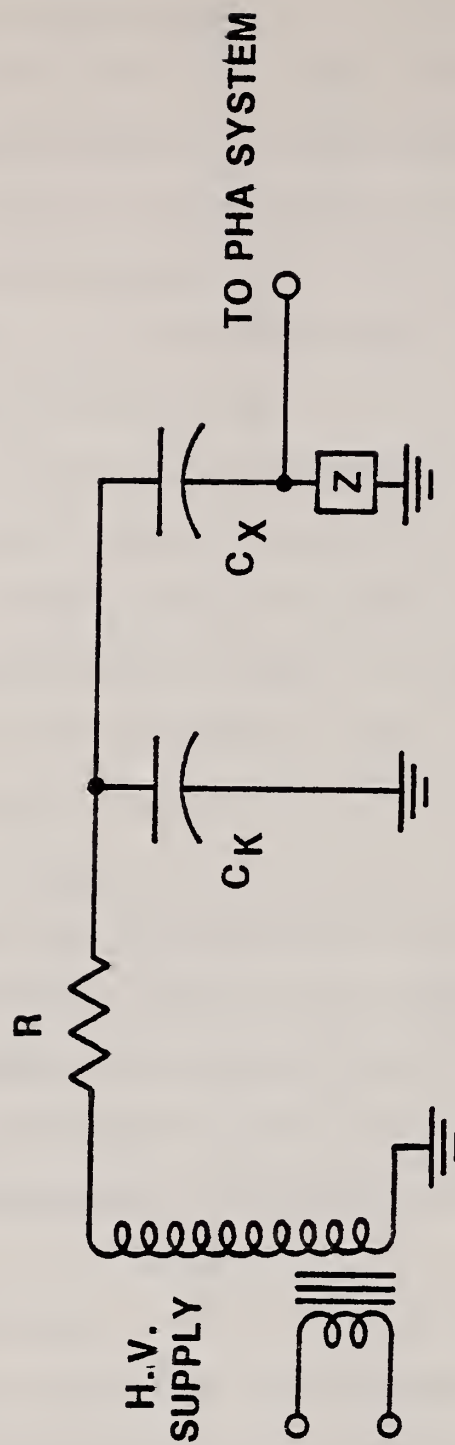


FIGURE A-1 High-voltage circuit for partial discharge measurements.

detection seemed impractical in this development system, however, and was not pursued. Instead of a balancing impedance, active circuitry was used, Fig. A-2, to inject a 60 Hz signal of adjustable amplitude and phase into one input of a differential amplifier Fig. A-3. The other amplifier input is derived from the corona detection impedance after being amplified by the wide-band FET preamplifier Fig. A-4. This preamplifier incorporates a high pass filter (cut-off frequency of 5 kHz) to also help reduce the effects of the applied voltage and the harmonics. The input of the 60 Hz buck-circuit can be connected to the primary of the supply transformer. Since the transformer itself generates harmonics, the buck-circuit is only useful for canceling out the 60 Hz component. An oscilloscope is used for this balancing, adjusting the phase and amplitude controls until the signal is zero (below the partial discharge inception voltage). Once the zero has been obtained no further adjustments are normally necessary over the transformer's working range. The presence of harmonics in the supply voltage ultimately limits the dynamic range of the PDMS. That is, partial discharges must appear larger than the sinusoidal harmonics in order to be observed.

B. Absolute Value Circuit

The partial discharge measurement system as it is now designed, measures the discharge magnitude and ignores the polarity of the discharge. The system could be easily modified to keep track of the discharge polarity. It would, however, necessitate a redesign of the peak and hold circuitry.

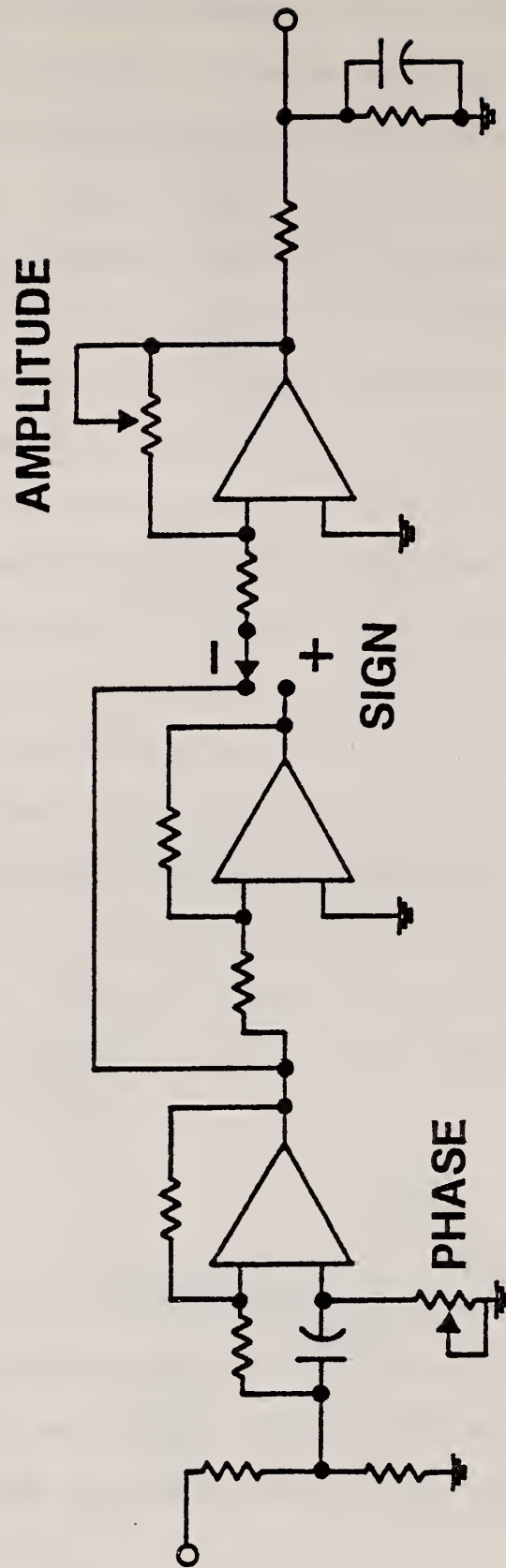


FIGURE A-2 Circuit for reducing 60-Hz common-mode voltage.

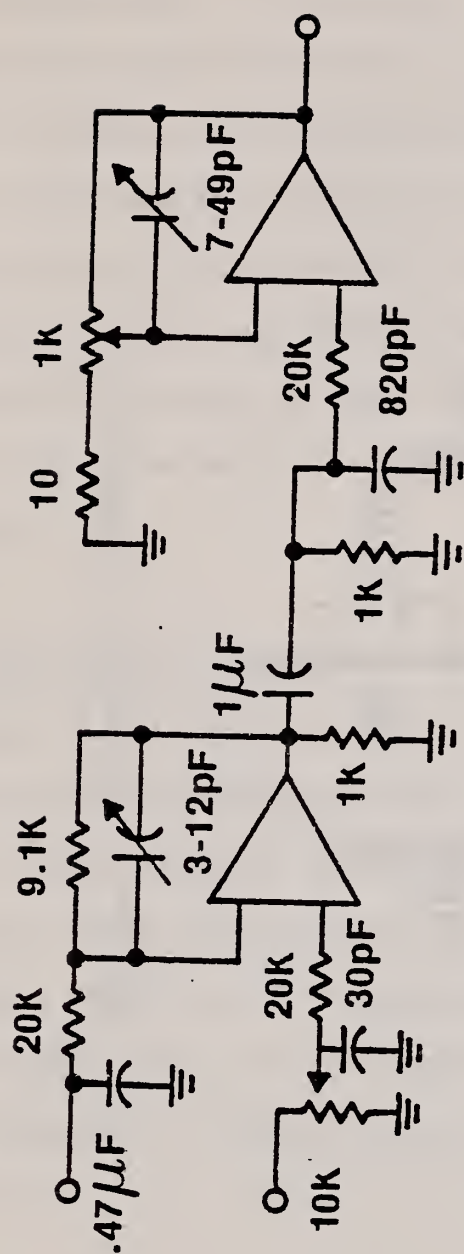


FIGURE A-3 Differential pulse amplifier.

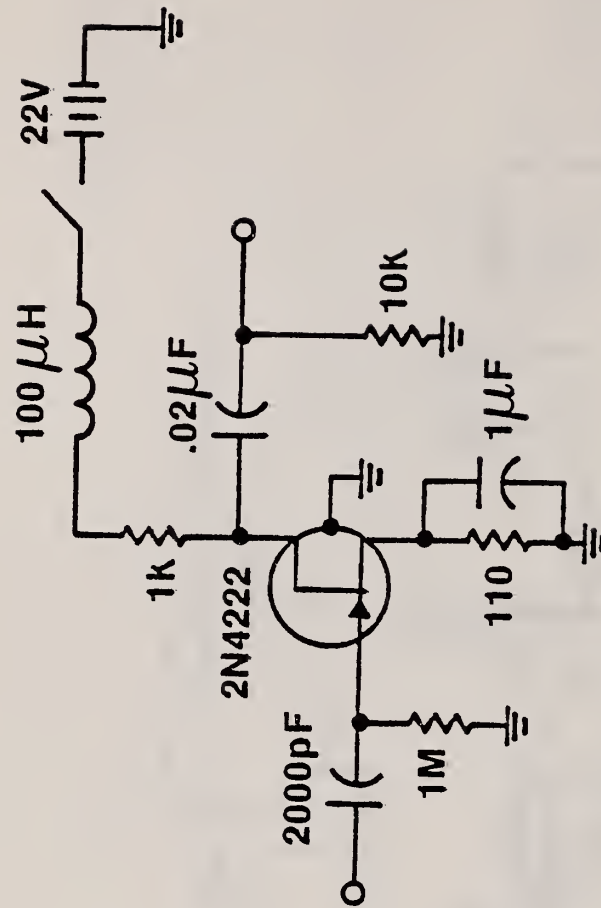


FIGURE A-4 Wide-band FET preamplifier.

The present system requires an absolute value circuit, Fig. A-5, to convert the bipolar pulses to negative pulses suitable for the peak-and-hold circuit. This circuit is basically an ideal diode circuit and an adder-subtractor. For positive input pulses diode D_1 conducts and D_2 does not so that the voltage, V_2 , is zero. The feedback variable resistor is adjusted so the output of the second operational amplifier is equal in magnitude but opposite in polarity to the positive input. For negative pulses, D_2 conducts and D_1 does not. The signal at V_2 is a positive pulse of equal magnitude to the input. The output of the adder-subtractor is minus two times the positive pulse plus minus one times the negative pulse or a negative pulse of equal magnitude to the input pulse.

C. Peak and Hold Circuit

The peak and hold circuit shown in Fig. A-6 is designed for a negative input pulse whose magnitude is less than 5 volts and whose duration is from 1 to 3 μ s. The purpose of the circuit is to hold the peaks of the voltage pulses and provide a signal to the peak and hold control logic when the peak is above some selectable threshold values. After the voltage pulse has been processed by the analog to digital converter and the minicomputer, the peak and hold circuit is reset for the next measurement.

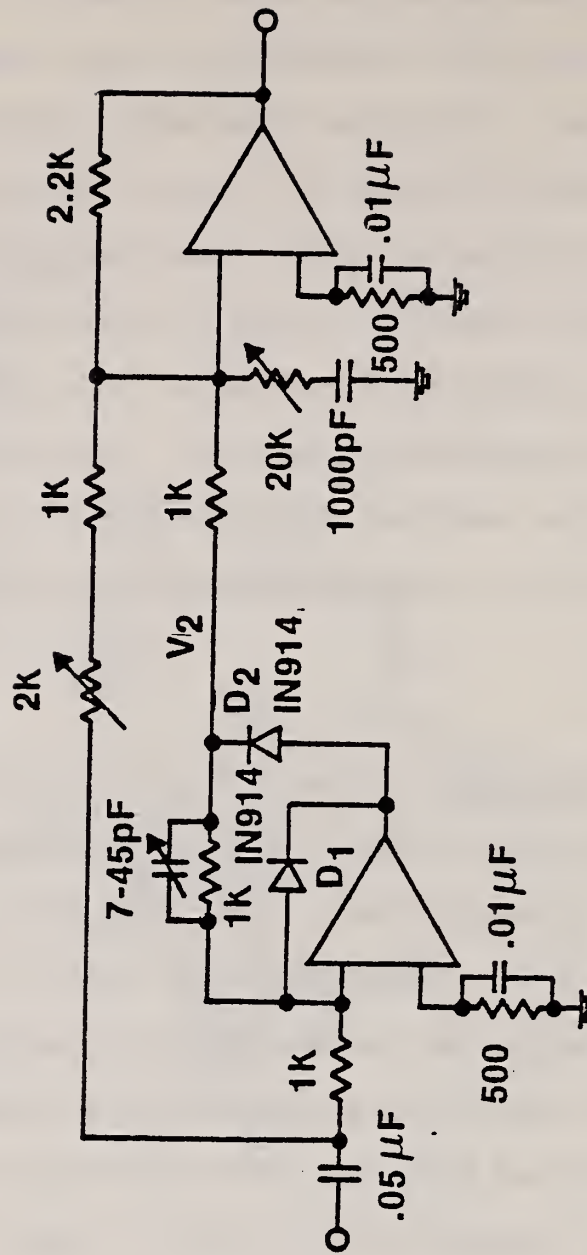


FIGURE A-5 Absolute-value circuit.

The basic peak and hold circuit consists of operational amplifiers A_1 , A_2 , and associated circuitry. With S_1 and S_2 open the circuit will follow the negative peaks. If e_1 is less than e_2 (and both less than zero), diode D_1 will conduct thereby charging the 500 pF capacitor. If e_1 is less negative than e_2 , diode D_1 will not conduct (and capacitor C will not discharge) but diode D_2 will conduct so that a feedback path is provided and A_1 will not lockup. A_2 must have a large input impedance in order to prevent the 500 pF capacitor from discharging. Amplifier A_3 provides a gain of 2 before the signal is sent to the analog to digital converter.

In order to prevent the system from being swamped by low-level noise signals a threshold circuit, A_4 , is used. The reference potential is adjusted by a 20-turn potentiometer. If the peak circuit is more negative than the threshold voltage the output of A_4 swings positive. This causes the inverter output (7406) to go low which causes the output of the positive NAND buffer (7438) to go high. This signal, START 1, indicates the presence of a partial discharge event of sufficient magnitude to be measured. START 1 is used by the peak and hold control logic (to be discussed below) to initiate the necessary chain of events for a discharge to be processed.

The peak and hold control logic, after allowing time for the discharge pulse to reach its peak value ($\sim 3 \mu s$), sends a hold signal back to the peak and hold circuit. This signal closes S_1 so that additional pulses cannot interfere. After the partial discharge has been processed

a RESET signal momentarily discharges the 500 pF capacitor, C, through switch S_2 , which grounds e_2 and causes START 1 to go low. The subsequent removal of the HOLD signal opens S_1 and thereby enables the peak and hold circuit.

D. Peak and Hold Control Logic

The peak and hold control logic is shown in Fig. A-7 along with the various signal levels. Input X104 is connected to the computer's general reset signal and on computer turn-on this signal (a low-level pulse) initializes the peak and hold control logic.

When START 1 goes high (indicating a discharge of magnitude greater than the threshold) the output of the positive-NAND Schmitt-trigger (7413) goes low. This does two things. First of all a low-level pulse is outputted from $\bar{Q}$ of the monostable multivibrator, M_4 . This goes to the preset of the J-K flip-flop, J_1 which sets $\bar{Q}$ low. This effectively causes the output of the positive-NAND Schmitt-trigger (7413) to return to the high state and stay there until the discharge pulse has been processed. Secondly it causes a high-level pulse to be outputted by Q of M_1 with a 3 μ s delay time to its trailing edge. This pulse does two things. First it causes the monostable multivibrator M_5 to output a low-level pulse which goes to the preset of the J-K flip-flop, J_2 . This causes $\bar{Q}$ of J_2 to go low which raises the HOLD signal. Also the output pulse of M_1 goes to M_2 which causes a high-level pulse to be outputted by Q of M_2 with a 1 μ s width and subsequently a high-level pulse out of Q of M_3 which results in a similar low level pulse at START 2 which goes to the analog-to-digital control logic circuit and starts the conversion process.

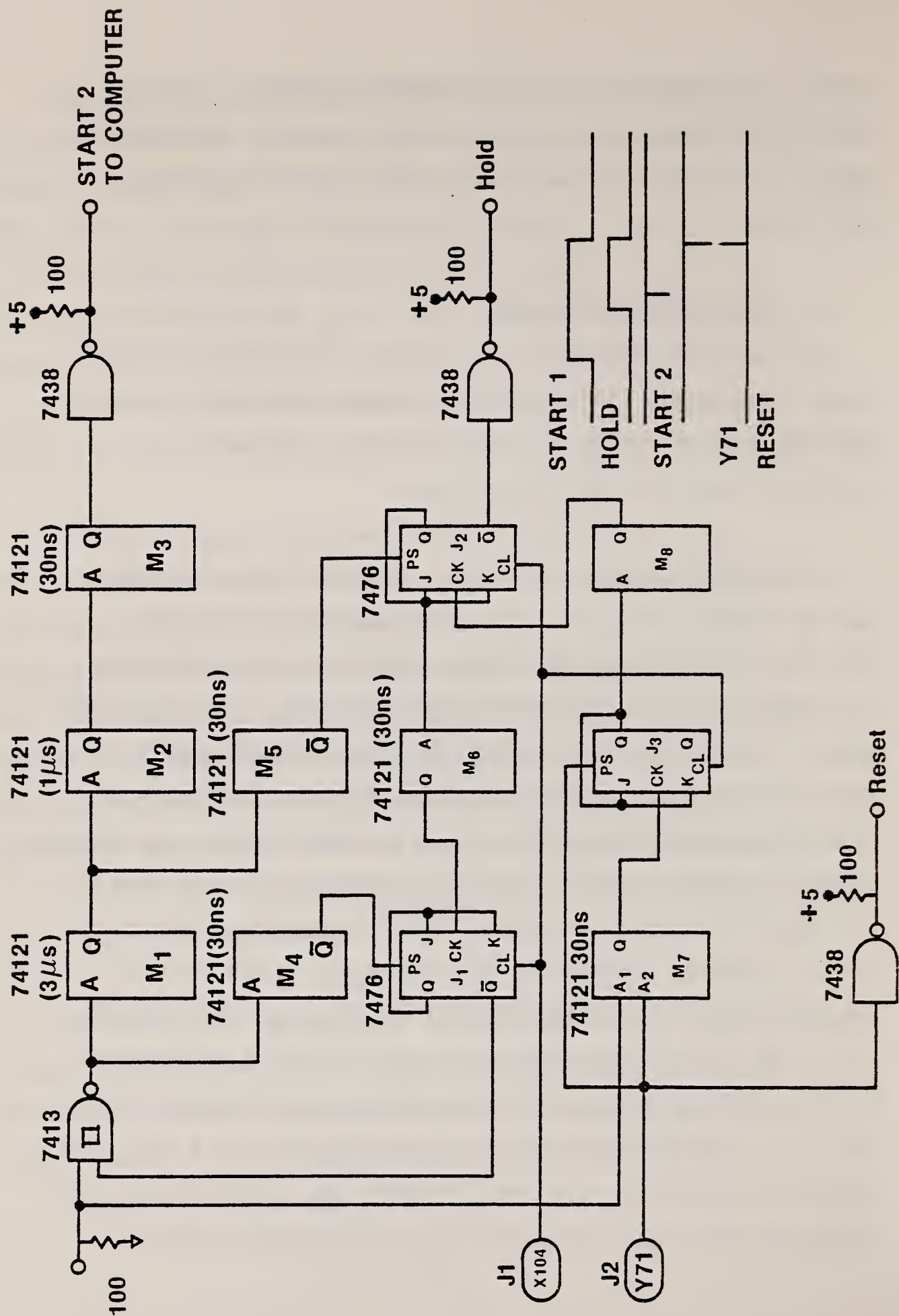


FIGURE A-7 Peak and hold control logic.

The hold signal stays high until a low-level pulse is returned on Y71 indicating that the data point has been read by the selector channel. This low-level pulse does several things. It causes a high-level pulse on RESET which partially enables the peak and hold circuit by zeroing the hold capacitor, C. The Y71 pulse also causes a high-level pulse at Q of M_7 . Since the clear, preset, J, and K inputs of J-K flip-flop J_3 are high (by the Y71 preset) the high level input clock pulse causes J_3 to toggle or Q to go low. This causes a high level output pulse at Q of M_8 . This pulse causes J-K flip-flop J_2 to toggle which results in the input of M_6 going low and the HOLD pulse going low. The removal of the HOLD signal opens switch S_1 of Fig. A-6 and enables the peak and hold circuit. A high level pulse is outputted from Q of M_6 which causes J_1 to toggle thereby causing $\bar{Q}$ to go high. This enables the next sizable pulse to trigger the 7413 positive-NAND.

E. Analog-to-Digital Control Logic Circuit

The control logic for the analog-to-digital converter is shown in Fig. A-8 along with the various signal levels. This circuitry is designed to give the analog-to-digital converter a suitable start signal, to notify the computer when the conversion is completed and data can be read, and to produce a signal level to indicate when the digital data has been read by the computer.

The low-level pulse, START 2, from the peak and hold control logic circuit causes a high level pulse to be outputted at Q of the retriggerable monostable multivibrator, M_1 . This output pulse is suitable to start the analog-to-digital converter. After the conversion process is completed

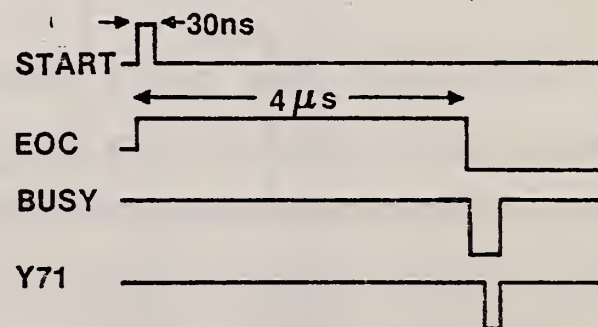
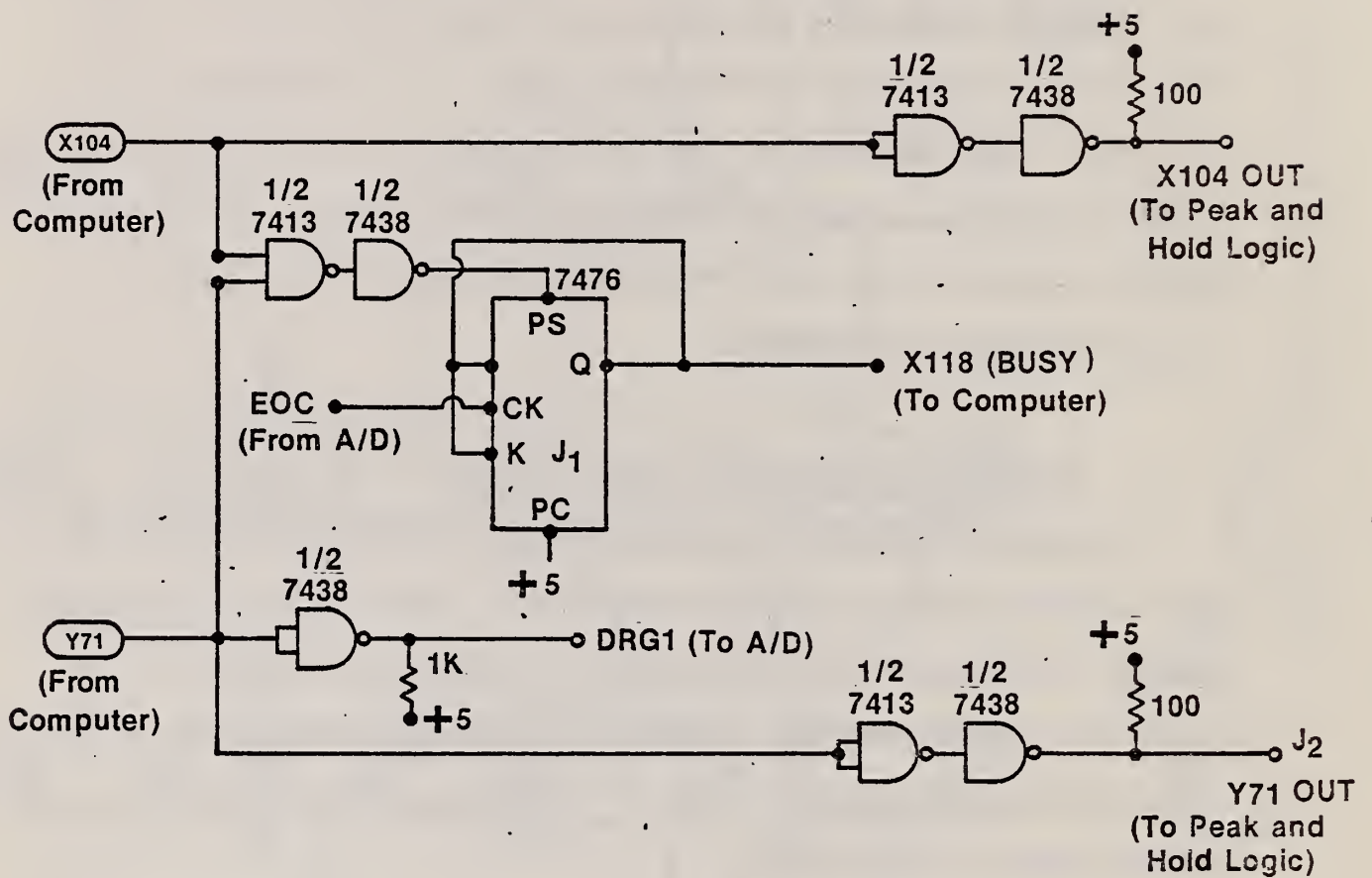
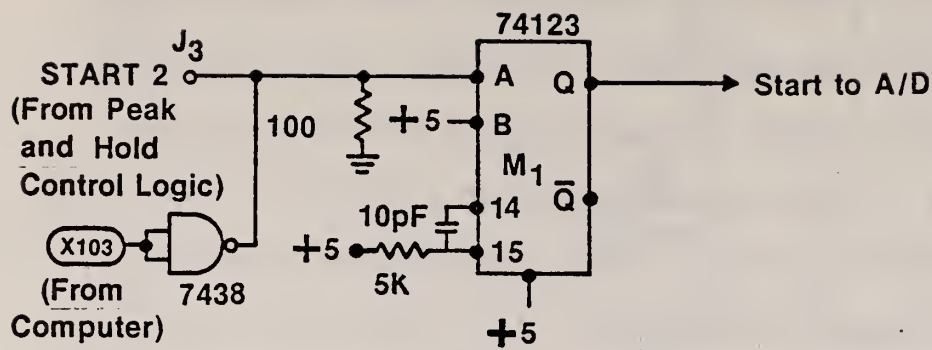


FIGURE A-8 A/D converter control logic.

the analog to digital converter sends the trailing edge of the positive pulse, EOC to the 7476 J-K flip-flop, J_1 . The output of this flip flop, Q, is initially high because of the preset going low caused by the X104 clear pulse. The EOC pulse causes the flip flop to toggle resulting in Q of J_1 and hence BUSY, (X118) going low. This tells the selector channel that data is ready to be read. If the computer is not busy the computer sends back the Y71 low-level pulse. This causes the flip-flop preset to again go low which causes J,K, and Q to go high. The Y71 also causes a high-level DRG1 pulse which strobes in the data. BUSY is again high and stays there until the next data point has been converted. If the computer is busy (exchanging buffers, for example), the Y71 low-level pulse will not be returned until the computer is not busy and the data point can be read. This means that the data point will not be lost. However, the peak and hold control logic will also not be reset until it sees the Y71 pulse so any additional discharges will not be measured. The Y71 pulse functions to keep other data from entering the peak and hold circuitry (and hence the analog-to-digital converter) until the previous data point has been completely processed. A convert command can be simulated by the computer by sending to the interface board any output command. This causes a high-level pulse at X103 which results in a low-level pulse at the A input of M_1 .

F. Analog-to-Digital Converter

The analog-to-digital wiring diagram is shown in Fig. A-9. The converter used is a DATEL* ADC-N12B2A with a conversion time of 4 μ s for a 12 bit binary output. In order to achieve the fast conversion time, the converter uses the technique of successive approximations. After receiving the START pulse from the analog-to-digital control logic,

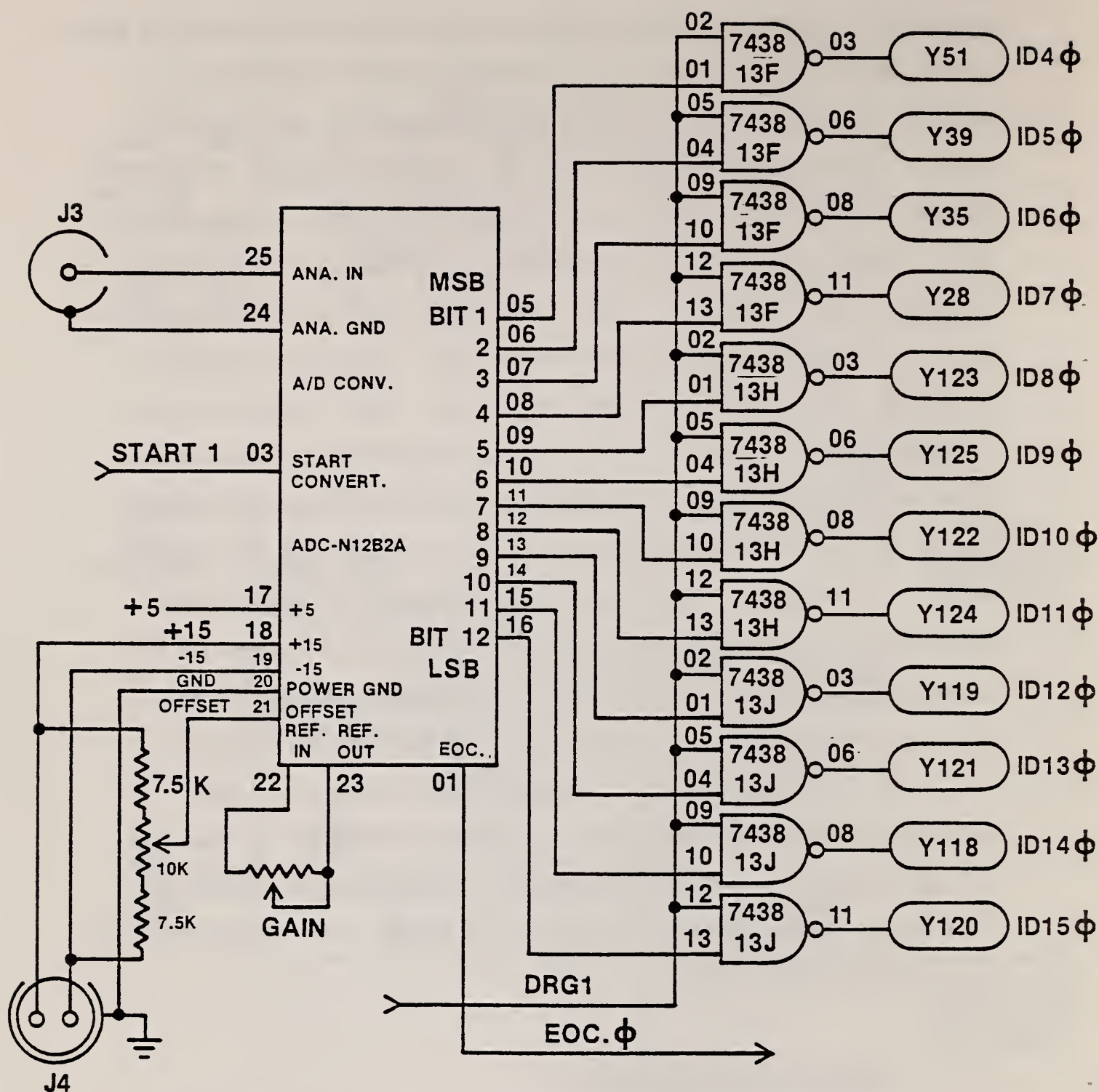


FIGURE A-9 Analog-to-digital converter interface circuit.

all the internal D/A switches are set to the off state except the most significant bit. The voltage level to be converted is compared to the analog equivalent of the most significant bit. If the voltage level is higher, the most significant bit is kept and if not, the bit is dropped. Next the voltage level is compared to the sum of the first choice and the second bit on. The process is completed at the rate of 220 ns per bit until all 12 bits have been determined. The EOC stays high until the conversion is completed. After the conversion is completed its trailing edge toggles the J_1 flip-flop on the analog-to-digital control logic circuit.

The input range of this analog-to-digital converter is 0 to -10 volts. The output format is straight binary. The 12 parallel data lines are strobed to the computer by the Y71 low-level pulse which results in the DRG1 high-level pulse. The converter has both a zero-offset adjustment and a gain adjustment. The manufacturer claims a long term stability for the converter of $\pm 0.1\%$ for six months and a linearity of $\pm 1/2$ least-significant-bit. The temperature coefficient is about ± 20 ppm/ $^{\circ}\text{C}$.

II. Software

The software will be first described in very general terms and later in this report the details will be presented. The main challenge is to gather data as fast as possible, sort it, and display it. The program must allow user intervention but without sacrificing the data acquisition rate. There are three distinct parts of the software: the main routine, the utility routines, and the data collection routines.

The data collection routines run independently of the others (except for the starting and stopping of the data collection routines) and have priority over anything else in the system. They are interrupt driven, which means they get control when a collection of data has been completed (i.e., data buffer is full). They use a double buffering scheme to insure that data collection always continues. The data collection routines process the input data quickly (i.e., sort it by amplitude and add it to data already collected) and return to whatever else was going on at the time of the interrupt (Fig. A-10).

The main routine consists of a simple main loop which displays the processed data, pauses for a time, displays again and so on. If the operator presses the escape key on the terminal, this loop is broken and the routine will now accept operator commands. After the operator command is acted on, the display loop is begun again. Meanwhile, during all this, the data collection goes on.

The utility routines do the work for the main routine such as: starting and stopping the data collection, drawing the display, varying the oscilloscope screen brightness, displaying characters, controlling the channels to be displayed, etc.

The utility and data collection routines are written in Assembler and the main routine is in BASIC.

A. Timing Constraints Imposed by Software and Processor

The maximum average rate of the data collection is determined by the time it takes to sort the contents of a filled data buffer while

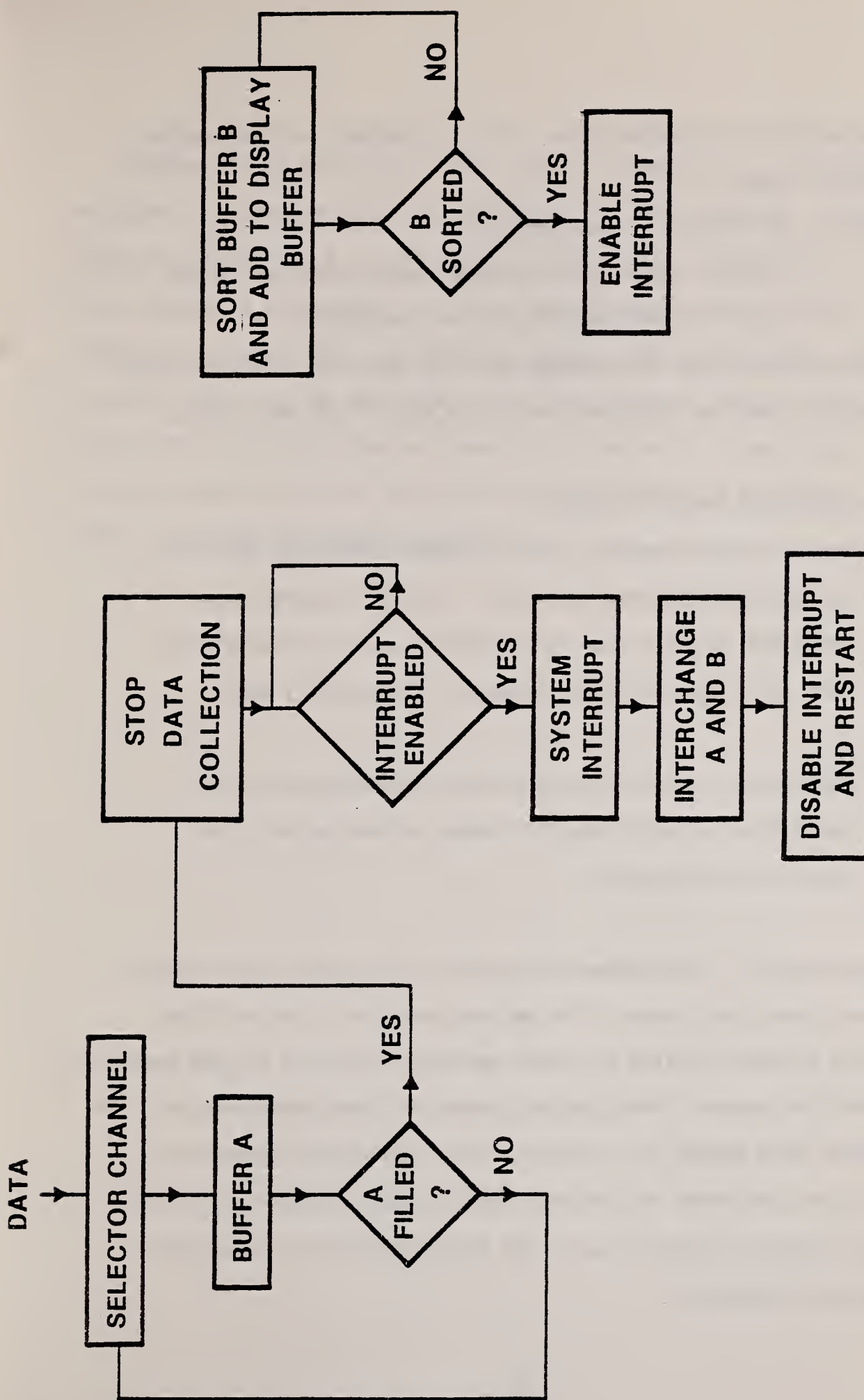


FIGURE A-10 Data collection logic diagram.

the other buffer is collecting data. In the interrupt service routine is found this loop:

```
LOOP      LH R15, 0(11) Load Data Point
          AHM R14, CHANL (R15) Increment Memory Location by One
          BXLE 11, LOOP Loops for Entire Data Buffer.
```

These three instructions are executed once for each data point collected.

The execution times for the three are $3.00 + 4.50 + 4.75$ or $12.25 \mu\text{s}$.

There are two other smaller effects:

- 1) For each buffer emptied, there is some overhead in setting up for the next buffer ($\sim 50 \mu\text{s}$). Typically there are at least 200 points in the filled buffer (user selectable) and each one's share in this overhead is consequently small.
- 2) While the interrupt service routine is running, the data collection is busily stealing memory access cycles, which can slow the processor.

Experimentally, the maximum average data acquisition rate is about 80,000 data points per second. The maximum burst rate (the rate that data can be properly handled for short periods of time) is 125,000 twelve-bit data points per second. The selector channel or direct-memory-access can transfer data points at a rate of 1 MHz. The limiting factor in bursts is the time taken for the peak and hold and the analog to digital circuits to cycle. Bursts of up to the number of points in the buffer can be properly handled.

Another timing constraint is the amount of dead time. After receipt of a partial-discharge pulse, the circuitry will not recognize a new pulse until after its 8 μ s cycle time (the burst rate limitation). Also, whenever a data buffer is filled, the selector channel will be inactive for a time while the new data buffer is being initiated. If one pulse enters during that time, it will be correctly handled (the peak and hold circuitry does not reset until the point is read) but successive pulses would be lost. The selector channel is inactive during the following command sequence:

Immediate Interrupt	8.00 μ s	Sent to interrupt service routines
STM 12, REGS+2	10.00	
LHI SELCH, SDA	1.50	
OC SELCH, SSTOP	4.50	Clear selector channel
RHR SELCH, R13	4.75	Get ending address
OC SELCH, SSTOP	4.50	Clear selector channel
WH SELCH, ASOB	5.75	Send new address
WH SELCH, AEOB	5.75	
LHI AD, ADDA	1.50	
SSR AD, R12	4.00	Access device
OC SELCH, SREAD	<u>4.50</u>	Start selector channel
	54.75 μ s	

In practice it is extremely rare that the partial discharge rate is so fast that data points are lost. There is usually a considerable amount of time during a 60-hertz cycle when partial discharge pulses are not being generated. For example, there are usually no discharges near the voltage zeroes except in the cases of discharge caused by poor contact.

The selector channel (or direct-memory-access) used for data input can transfer data to memory at up to 2 megabytes/s. (One byte is equal to 8 bits). The selector channel has two registers: current address and final address. The selector channel attempts to raise an interrupt when it has filled the final address.

While the selector channel is filling up one buffer, A, with new data, the other buffer, B, is being processed. For each data point in buffer B, the appropriate channel in the display buffer is incremented by one. The interrupt from the selector channel will not be raised until buffer B is done being processed. If buffer B is still being processed when the selector channel has finished filling buffer A, new data may be lost and the message "Possible Lost Data" will be printed on the system console when there is time. If buffer B is done being processed when the selector channel interrupt is raised, the two buffers are quickly interchanged ($\sim 55 \mu s$) and data collection continues. As mentioned above it is extremely rare in practice that the data sorting cannot keep up with the data collecting.

Once the selector channel interrupt has been handled, the control will revert to the main program which will keep displaying the updated data on the oscilloscope. If there is channel overflow ($> 32,767$ counts in a channel), data collection will be halted. No information is lost; the data can be outputted to a floppy diskette and the experiment started over again.

B. Operator Commands

The operator commands allow user interaction with the partial discharge measurement system. They are entered by hitting the "escape key" and then at least the first two letters of the appropriate command. The escape key causes an error which temporarily breaks the loop in the BASIC main routine. The command is then read and if necessary the

appropriate utility routine is called to execute the command. If the data collection rate is high, the system will temporarily ignore the new operator command since the data collection has top interrupt priority. All commands will be executed, however, when there is sufficient free time. Listed below are the current operator commands and what they explicitly do. New commands can easily be added.

OPERATOR COMMAND LIST

- GO - Begins the collection of data
- COUNT - Prints the total number of data points collected
- HALT - Stops the collection of data
- RESUME - Continues a run after HALT
- END - Ends a run, writes data to floppy diskette
- ABORT - Stops a run
- SELECT [N,M] - Display channel N to M, if no operand writes on system console the N and M in use
- PRINT N,M - Prints on the system console all the nonzero channels and their contents from N to M
- TOGGLE - Toggles data collection buffers (i.e., forces buffers A and B to interchange thereby allowing the display of a non-filled buffer)
- BASIC - Stops main routine and returns to BASIC compiler
- BUFFERSIZE [N] - Sets buffersize to N, if no operand prints buffersize currently in use (500 is the default size)
- BRIGHT - Intensifies display
- LOW - Dims display
- DISPLAY - Displays a standard test pattern for adjusting the oscilloscope

DVM - For testing the analog to digital converter, +5 volts in series with 1 k Ω required on "start", 0 - -10 Vdc required on "data", reading displayed on minicomputer front panel meter in hexadecimal

INFO [N] - Writes information (run number, calibration, channels being displayed) on screen in quadrant N. If no operand, writes in first quadrant

NOINFO - Removes information from screen

C. Detailed Software Description

The software was specifically written for an Interdata* 7/16 minicomputer. The detailed software presentation that follows should enable the software to be modified for other machines.

1. BASIC Main Routine

This routine has three main functions:

a) Waste time by executing the loop:

```
FOR I=1 TO D1
```

```
NEXT I
```

where D1 is currently set for 700 (statements 90, 800, 810).

b) Update the display, if data collection is going on (statements 620-850).

c) Handle commands from the operator.

If the operator hits the "escape" key on the system console, an "ES" BASIC error results (statements 20, 1140, 1150) which causes a transfer due to the ON ERROR TO statement. Then an operator command is read, and a transfer is made to the appropriate section (1250-1590). If

```

10 R=40
20 ON ERROR GOTO 1140
30 GOTO R
40 DIM C$(2)
50 B=500
60 T=B
70 DIM B1(B/2),B2(B/2)
80 N=1023
90 D1=700
100 DIM C(N),D(N+5)
110 DIM S$(11),T$(10)
120 S$="0.0000000000000000 "
130 T$=S$
140 DIM L$(65)
150 L$=S$+S$+S$+S$+S$+S$+S$
160 DIM Q$(1),E$(2)
170 FOR I=0 TO N+5
180 D(I)=0
190 NEXT I
200 I1=1
210 S1=0
220 S2=N
230 U=3
240 W=0
250 S=0
260 X1=9
270 Y1=11
280 P5=0
290 S5=0
300 O1=0
310 O2=0
320 O3=0
330 DIM L(4,2)
340 MAT READ L
350 DATA 0,1433,-1842,1433,-1842,0,0,0
360 DIM A$(80),O$(10)
370 READ P1
380 DIM P(P1)
390 FOR I=1 TO P1
400 READ P(I)
410 NEXT I
420 DATA 31,0
430 DATA 10,20,30,40,50,60,70,80,90
440 DATA 100,200,300,400,500,600,700,800,900
450 DATA 1000,2000,3000,4000,5000,6000,7000,8000,9000
460 DATA 10000,20000,30000
470 CALL 1007,P(1),P1
480 ;"RUN NUMBER?"
490 INPUT N5
500 ;"CALIBRATION? (PC) "
510 INPUT S5
520 ;"AT CHANNEL?"
530 INPUT S4
540 IF S4=0 GOTO 570
550 S5=S5/S4

```

```

560 GOTO 590
570 S5=0
580 REM
590 CALL 1026,E
600 IF E<>0 GOTO 870
610 IF S=0 GOTO 590
620 IF P5<=0 GOTO 780
630 X=L(P5,1)
640 Y=L(P5,2)
650 A$="RUN <35>" +STR$(N5)
660 CALL 1001,A$,X,Y,X1,Y1,I1
670 Y=Y-13*Y1
680 IF S5=0 GOTO 760
690 S7=100*S1*S5
700 S7=INT(S7)/100
710 S8=100*S2*S5
720 S8=INT(S8)/100
730 A$="RANGE " +STR$(S7) + "-" +STR$(S8) + " PC"
740 CALL 1001,A$,X,Y,X1,Y1,I1
750 Y=Y-13*Y1
760 A$="CHANNELS " +STR$(S1) + "-" +STR$(S2)
770 CALL 1001,A$,X,Y,X1,Y1,I1
780 CALL 1008,S1,S2,I1
790 CALL 1005
800 FOR I=1 TO D1
810 NEXT I
820 GOTO 590
830 IF E<>0 GOTO 870
840 CALL 1005
850 GOTO 620
860 REM
870 IF E=1 GOTO 910
880 IF E=2 GOTO 930
890 IF E=3 AND S GOTO 950
900 GOTO 590
910 : "ERROR ON SELECTOR CHANNEL "
920 GOTO 840
930 : "POSSIBLE LOST DATA"
940 GOTO 590
950 : "CHANNEL OVERFLOW, DATA COLLECTION HALTED"
960 CALL 1005
970 CALL 1008,S1,S2,I1
980 CALL 1005
990 CALL 1026,E
1000 IF E<>0 GOTO 990
1010 : "KEEP CURRENT DATA? (Y OR N)"
1020 INPUT Q$
1030 IF Q$<>"Y" GOTO 1080
1040 CALL 1024,C(0)
1050 FOR I=0 TO N
1060 D(I)=D(I)+C(I)
1070 NEXT I
1080 : "COLLECT MORE DATA? (Y OR N)?"
1090 INPUT Q$
1100 IF Q$="Y" GOTO 1710

```

ERRORS FROM ASSEMBLER ROUTINES

```

1110 S=0
1120 GOTO 600
1130 REM
1140 C$=ERR$(0)
1150 IF E$="ES" GOTO 1250
1160 IF E$="IN" GOTO 1600
1170 IF E$="SB" GOTO 1600
1180 IF E$="UF" GOTO 2410
1190 IF E$>"IO" GOTO 1220
1200 IF W GOTO 2540
1210 GOTO 2070
1220 :ERR$(0):"ERROR, LINE";ERL(0)
1230 STOP
1240 REM
1250 INPUT A$
1260 C$=A$
1270 M=LEN(A$)
1280 B1=M
1290 C1=M+1
1300 O3=0
1310 FOR I=M TO 1 STEP -1
1320 IF A$(I,I)="" THEN B1=I
1330 IF A$(I,I)=", " THEN C1=I
1340 NEXT I
1350 IF B1=M GOTO 1430
1360 O3=1
1370 O$=A$(B1+1,C1-1)
1380 O1=VAL(O$)
1390 IF C1>M GOTO 1430
1400 O3=2
1410 O$=A$(C1+1,M)
1420 O2=VAL(O$)
1430 IF C$="HA" GOTO 1630
1440 IF C$="TO" GOTO 1680
1450 IF C$="AB" GOTO 1630
1460 IF C$="EN" GOTO 2590
1470 IF C$="GO" GOTO 1710
1480 IF C$="PR" GOTO 1760
1490 IF C$="RE" GOTO 1850
1500 IF C$="CO" GOTO 1900
1510 IF C$="SE" GOTO 1980
1520 IF C$="BA" GOTO 2070
1530 IF C$="BU" GOTO 2100
1540 IF C$="BR" GOTO 2180
1550 IF C$="LO" GOTO 2210
1560 IF C$="DI" GOTO 2290
1570 IF C$="DV" GOTO 2240
1580 IF C$="IN" GOTO 2460
1590 IF C$="NO" GOTO 2510
1600 : "INVALID COMMAND"
1610 GOTO 600
1620 REM
1630 CALL 1021
1640 : "DATA COLLECTION HALTED"
1650 S=0

```

```

1660 GOTO 840
1670 REM
1680 CALL 1023
1690 GOTO 830
1700 REM
1710 ;"DATA COLLECTION BEGUN"
1720 S=1
1730 CALL 1020,T,B1(0),B2(0)
1740 GOTO 830
1750 REM
1760 IF 03<>2 GOTO 1600
1770 CALL 1024,C(0)
1780 FOR I=01 TO 02
1790 IF C(I)=0 GOTO 1810
1800 ;I;"-";C(I)
1810 NEXT I
1820 ;"CHANNELS";01;"-";02;"WERE SCANNED FOR PRINTING"
1830 GOTO 600
1840 REM
1850 ;"DATA COLLECTION RESUMED"
1860 S=1
1870 CALL 1022
1880 GOTO 830
1890 REM
1900 CALL 1024,C(0)
1910 C1=0
1920 FOR I=0 TO N
1930 C1=C1+C(I)
1940 NEXT I
1950 ;C1;"POINTS COLLECTED"
1960 GOTO 600
1970 REM
1980 IF 03=2 GOTO 2010
1990 ;"CURRENTLY SET TO DISPLAY CHANNELS";S1;"-";S2
2000 GOTO 600
2010 S1=01
2020 S2=02
2030 IF S1<0 OR S1>N THEN S1=0
2040 IF S2<N OR S2<S1 THEN S2=N
2050 GOTO 830
2060 REM
2070 ;FNA(0)
2080 GOTO 600
2090 REM
2100 IF 03=1 GOTO 2130
2110 ;"BUFFERSIZE IS";T
2120 GOTO 600
2130 T=01
2140 IF T>B THEN T=B
2150 ;"USE COMMAND GO TO PUT NEW BUFFERSIZE INTO EFFECT"
2160 GOTO 600
2170 REM
2180 I1=3
2190 GOTO 830
2200 REM

```

TO

GO

PR

COU

SEL

PAU

BRI

95

DIM

```

2210 I:=1
2220 GOTO 600
2230 REM
2240 CALL 1021
2250 CALL 1002
2260 GOTO 2250
2270 GOTO 600
2280 REM
2290 CALL 1005
2300 FOR I=5 TO -5 STEP -1
2310 X=INT(I*409.4)
2320 FOR J=-4 TO 4
2330 Y=INT(J*409.4)
2340 CALL 1003,X,Y,I
2350 NEXT J
2360 NEXT I
2370 ; "ADJUST DISPLAY PLEASE"
2380 S=0
2390 CALL 1005
2400 GOTO 600
2410 R=ERL(0)+10
2420 ; "TYPE <34>RUN 20<34> TO CONTINUE"
2430 STOP
2440 GOTO 20
2450 REM
2460 P5=ABS(01)
2470 IF 03=0 THEN P5=1
2480 IF P5>4 THEN P5=4
2490 GOTO 830
2500 REM
2510 P5=0
2520 GOTO 830
2540 ; "ERROR IN WRITING TO UNIT";U
2550 W=0
2560 ; FNA(0)
2570 GOTO 2690
2580 REM
2590 CALL 1021
2600 ; "DATA COLLECTION ENDED"
2610 ; "KEEP CURRENT DATA? (Y OR N)"
2620 INPUT Q$
2630 IF Q$<>"Y" GOTO 2680
2640 CALL 1024,C(0)
2650 FOR I=0 TO N
2660 D(I)=D(I)+C(I)
2670 NEXT I
2680 ; "ALL SAVED DATA WILL BE WRITTEN TO LOGICAL UNIT";U
2690 ; "IS LOGICAL UNIT";U; "READY? (Y OR N)"
2700 INPUT Q$
2710 IF Q$="Y" GOTO 2740
2720 ; FNA(0)
2730 GOTO 2690
2740 W=1
2750 PRINT ON (U) USING T$,N5
2760 PRINT ON (U) USING T$,S5

```

DVM

DISPLAY

INFO

NO INFO

END

```
2770 FOR I=0 TO N STEP 6*
2780 PRINT ON (U) USING L$,D(I),D(I+1),D(I+2),D(I+3),D(I+4),D(I+5)
2790 NEXT I
2800 WFM U
2810 W=0
2820 END
```

the command is invalid, a message is printed and the routine returns to the main loop (1600-1610). This escape strategy rules out using GOSUB and RETURN because an escape could interrupt execution in the middle of a subroutine and there would be no way to know where to return.

The commands are broken up into a two-character variable, C\$ (being the first two letters of the command), a variable telling the number of operands (O3), and the operands (O1 and O2) if present. The commands are straightforward, execution typically being accomplished by calls to a utility routine. A flag variable, S, tells whether data collection is going on. If no data are being collected, the display is not continually updated.

The END command causes the collected data to be written to a floppy diskette. The run number, sensitivity, and the contents of the 1023 channels are outputted. The run number and sensitivity are written on the first two records in an E10.4 format. The channels are written, 6 per record, in a (5(E10.4, 1X), E10.4) format. Each diskette track contains 16 sectors or 288 channels (3 records per sector) so that an entire run can be stored on 4 tracks. This implies that seventeen runs could be stored on each side of a diskette. The current format is chosen because each number has exactly one space between it and its neighbor and no spaces occur at the end of a line, so BASIC can read the file. It is also a fixed field format (the numbers always fall in the same columns) so FORTRAN can read the file.

If a data-related error is detected, a message is printed (statements 590, 870-950). Data collection is not halted on a selector channel error or a lost data error. For a channel overflow error data collection is halted. The main routine then asks whether the data collected should be saved. If so, the data are added into the data previously collected (if any). Therefore, on channel overflow no information is lost -- not even from the channel which overflowed (statements 950-1070).

The return to the BASIC host environment, either due to the operator command "BASIC" or because the operator responded "no" when asked if the output device is ready, is accomplished by causing an undefined function error (statements 20, 30, 1180, 1520, 2070, 2410, 2420, 2720). The next statement to be executed is found by adding 10 to the line number of the statement which caused the error. This number is stored, variable R, and a stop issued. The operator continues operation with a "RUN 20", which reinstates the "ON ERROR GO TO" statement (which is killed by the "STOP") and branches to statement number R.

2. Data Collection Routines (statements 94-161 of Assembler Language Listing)

Upon selector channel interrupt, control is transferred to this routine by way of the immediate interrupt sequence. Three steps occur in this transfer: (1) the old Program Status Word (PSW) is saved at location ISR, (2) the new PSW status part is loaded from ISR+4 (X '2000' is loaded), and (3) the location counter is set to ISR+6 (at the start of the program). The new PSW has locked out all interrupts except

machine malfunction. This does not mean interrupts occurring during this time will be lost; they are just not acknowledged. When a normal PSW status is restored any pending interrupts will occur. When this routine is running nothing (except a machine malfunction) will interrupt it.

The ISR or data collection routine has two specific duties. The first is to restart the selector channel on a new buffer as quickly as possible. A double buffer technique is used where one buffer is given to the selector channel to fill while the other one is being processed. When the one is filled, their roles are exchanged. The error checking and actual buffer exchange are postponed until the selector channel is restarted. The ending address of the selector channel is read and compared to the expected ending address. If they do not agree, some selector channel error has occurred.

The second duty is to process the data buffer just filled by the selector channel. The selector has read numbers off the analog-to-digital converter in the range 0-4095 (12-bit converter). This number is used directly as an index into the channel array. The channels array is 2048 halfwords (4096 bytes) long. (On the Interdata machine an address which is not on a halfword boundary is truncated to be on a halfword boundary thereby effectively compacting the data. Each halfword location thus indexed is incremented by one).

The routine senses two error conditions. The selector channel error occurs when the address of the selector channel stopping point is different from that expected indicating a premature halt. Variable SFLAG is set on

this error. The possible lost data error occurs when the selector channel has finished collecting a new buffer of data before the old buffer has been processed. This condition is detected in the following way. Suppose the selector channel has finished during processing (it will not interrupt the processing because interrupts are disabled). As soon as the interrupts are enabled it will interrupt. During this time span it is inactive and data would be lost. So if the processing routine is ever re-entered with a return address of the last statement of the processing routine then this situation has occurred and variable LOST is set on this error. "POSSIBLE LOST DATA" usually means too high a rate of input data. Increasing the buffer size thereby decreasing the dead time could help if the rate is only slightly too high. Having the buffer size too large, however, results in long waits before collected data is displayed. Note that it is not desirable to print an error message at the time this error occurs because then is precisely when all activity should be directed towards collecting and processing data.

3. Utility Routines

There are a number of utility routines. Some are executed using calls from BASIC. Others are used in the execution of different routines.

a. Name: DVM

Calling Sequence: CALL 1002

Operands: None

Purpose: To check the A-to-D (analog-to-digital) converter.

Each call to this routine causes an output command to be sent to the A-to-D board triggering a conversion then reading the converted value and displaying it on the hexadecimal display panel.

The start input (see hardware section) must have +5 volts in series with 1 k Ω placed on it. The data input should have a dc level from 0 to -10 volts. The 10 most significant bits of the A-to-D are displayed giving numbers from 0 to 1023 but in hexadecimal (0 - 3FF).

b. Name: STRT

Calling Sequence: CALL 1020, N, B1(0), B2(0)

Operands: N is the number of halfwords in each buffer (each array element in BASIC consists of 2 halfwords)
B1 and B2 are arrays to be used as buffers, each N halfwords long. These are the input buffers used in the double buffering scheme. (Zero indexing is suggested for B1 and B2 so that the case N=1 will be handled without a problem).

Purpose: To begin data collection.

This routine sets up the interrupt service table to handle interrupts from the selector channel. The operating system has set bits 1 and 4 of the PSW, so when an interrupt occurs, it is handled as an immediate interrupt. That is, an interrupt causes the processor to send out an acknowledge interrupt signal. The first device (often the only device) on the interrupt chain which is in an interrupt state responds by giving its device number. The processor takes this number and uses it as an

index into the interrupt service table, retrieving from the table the address of the interrupt service routine for that device. The routine sets up an entry in the table so that a selector channel interrupt will be sent to routine "ISR".

This routine also zeros out the channels (CHANL) where the collected data is accumulated, stores the addresses of the starting and ending points of the two buffers (ASFB, AEFB, ASOB, AEOB), and calls routine "RESUME" which starts the selector channel.

c. Name: RESUME

Calling Sequence: CALL 1022

Operands: None

Purpose: To start the selector channel, used in commands
GO and RESUME.

This routine sets the A-to-D board to halfword mode, initializes the A-to-D logic with a READ, and starts the selector channel. It locks out interrupts for a time using an exchange program status command. This is necessary because the selector channel accesses the device last addressed on the private bus before the selector channel was started. If another device interrupted at the wrong time, the selector channel would be reading from that device instead of the A-to-D board.

d. Name: CLOSER

Calling Sequence: Set RESTART to 0 or 1

BAL 14, CLOSER

Operands: None

Purpose: To stop the selector in the middle of a buffer,
and possibly to restart it, used in HALT,
TOGGLE, END, ABORT. Command affected variables:
CHANL, ASFB, ASOB, AEFB, AEOB.

If RESTART = 0, the selector channel is not restarted. The code is similar to the interrupt service routine (ISR). Interrupts are shut out with an exchange program status command. Only the part of the buffer filled is processed into the channels. Note that this routine clears the interrupt caused by halting the selector channel.

If the selector channel is already stopped, this routine does nothing.

e. Name: HALT

Calling Sequence: CALL 1021

Operands: None

Purpose: To halt data collection

Affected Variables: RESTART.

This routine makes a call to routine CLOSER with RESTART set to 0. The selector channel is not restarted.

f. Name: TOGGLE

Calling Sequence: CALL 1023

Operands: None

Purpose: To halt data collection and resume it immediately,
this is to cause processing of data collected in a
buffer that has not yet filled.

This routine makes a call to routine CLOSER with RESTART set equal to 1.

g. Name: DATA

Calling Sequence: CALL 1024 C(0)

Operands: C is an array dimensioned C(1023) into which the channel counts will be placed. The channels are stored internally in array CHANL in I*2 form (halfword integer). They are converted to R*4 (fullword real numbers).

Purpose: To make the channels available to the BASIC main routine for calculations or printing.

This routine takes each adjacent pair of the 2048 channels, sums them and converts the sums to real numbers giving 1024 actual channels. Negative numbers are treated as large positive numbers permitting channel overflow to occur without any information being lost.

h. Name: ERROR

Calling Sequence: CALL 1026,E

Operands: E-Error code, will be set to:

- 0 - no error,
- 1 - error on selector channel,
- 2 - possibility of lost data,
- 3 - channel overflow.

Purpose: To communicate errors raised to the main program.

Affected Variables: LOST, OVER, SFLAG

This routine checks the error flags LOST, OVER, and SFLAG (in that order) to see if those flags have been raised. After setting E to reflect an error, the error flag involved is cleared.

j. Name: PLOTR and PLOTI

Calling Sequence: CALL 1003, X, Y, I

or BAL 14, PLOTI

Operands: X and Y - the X and Y values in the range -2047 to 2047,
I - the intensity (1-dim, 2-off, 3-bright).

Purpose: To plot an X and Y pair.

Affected Variables: MANY, BLOCK

PLOTR is for a call from BASIC with real number arguments. PLOTI is for calls from other Assembler routines. Return register for both is register 14 and register 15 points at the parameter address list.

This routine converts the numbers into numbers suitable for the dual D-to-A (which outputs to an oscilloscope display) and sets them into a buffer. If the buffer is filled, it is automatically dumped by a CALL 1005 or CALL 1006 to be displayed. If an X value is repeated from point to point, the X being unnecessary, is left out the second time.

j. Name: DUMP and LOOK

Calling Sequence: CALL 1005 for DUMP

CALL 1006 for LOOK

Operands: None.

Purpose: To dump the plot buffer to the display, DUMP resets the buffer to be empty and LOOK does not.

This routine does the actual plotting. The sequence is as follows:

- turn on the bus,
- set the mode of the dual D to A,
- set the memory to sequential mode,
- write the plot buffer to memory,
- set the memory to external mode (to continuously sweep through memory to the D to A).

Most of these operations are done with supervisor calls available in the Interdata* operating system.

k. Name: SIDES

Calling Sequence: CALL 1007,P(1),N

Operands: P - an array of Y values to be plotted on the left side of the display as a reference,
N - the dimension of P, N less than 50.

Purpose: To set up the margin display.

Affected Variables: SIDE, NSIDE

This routine is necessary only because the main histogram drawing routine is written in Assembler. This routine takes a list of Y values, converts them from R*4 as they are in BASIC to I*2 and stores them.

.l. Name: SLAP

Calling Sequence: CALL 1008, S1, S2, I

Operands: S1 - the starting channel to be plotted,
S2 - the ending channel to be plotted,
I - the intensity (1-dim, 2-off, 3-bright).

Purpose: To plot the histogram of the channels.

Affected Variables: OVER

This routine makes a quick copy of the channels which is necessary since they are constantly changing. It then scales the histogram to fit on the display using variable LEFT (the direction of the shift) and CONS (the magnitude of the shift). The channel with the largest count in the range of channels S1 and S2 will be scaled to be in the upper half of the display (unless all channels are empty).

The margin display undergoes the same scaling as the main display. If a margin point winds up off screen, it is simply not plotted.

This routine can raise the error "CHANNEL OVERFLOW". Suppose during the data accumulation, more points (> 32767) than an I^*2 variable can hold are collected in one channel. This is no real problem for the addition hardware treats an I^*2 variable as if it were unsigned (e.g., $7FFF_{16}[32767_{10}] + 1 = 8000_{16}[32768_{10}]$ and so on). The other instructions will recognize 8000_{16} as a negative number (the sign bit is on). This is the way an overflow condition is detected. No information is lost if we treat this number as unsigned. However, once overflow has occurred, data collection should be halted. Channel overflow indicates either too much data or, a dc input to the A-to-D, or positive pulses. Channel overflow

is not checked during data collection because too much time would be wasted. This routine would be better written in a higher language if floating point hardware were available. It is in Assembler to take advantage of the shift instructions which provide a very fast way of multiplying and dividing by powers of two.

m. Name: MFIX

Calling Sequence: BAL 15,MFIX

Operands: Floating point register 0 contains the input and register 0 contains the output.

Purpose: This routine converts a R*4 number to I*2, numbers in the range -32767 to 32767 are converted correctly.

This routine uses the method of adding an unnormalized zero to the number which yields an unnormalized result. The I*2 equivalent is the least significant 4 bytes.

Consider floating point 2:

41200000.

Add 46000000 (unnormalized zero), result is:

46000002.

This is still floating point but unnormalized. The second half can be picked off as fixed point 2. Negative numbers will have their two's complement taken.

n. Name: MFLOAT

Calling Sequence: BAL 15,MFLOAT

Operands: Register 0 contains the input, floating point
register 0 contains the output.

Purpose: To convert an I*2 number to R*4.

This routine uses the method of creating an unnormalized number.

Consider fixed point 2:

0002.

If the halfword 4600 is placed in front of it, the number becomes:

46000002

which is floating point two unnormalized. The LE command (load floating point) automatically normalizes the number. Negative numbers are complemented and the sign bit set. Both MFIX and MFLOAT are faster than the corresponding FORTRAN routines.

o. Name: WRITE

Calling Sequence: CALL 1001,N\$,X,Y,X1,X2,I

Operands: N\$-- character string to be written,
X and Y-- the X and Y location of where to
begin the string in the range -2047 to 2047,
X1 and Y1-- the spacing between dots in the
letters in the X and Y directions, this
determines the size and proportion of the letters,
and I-- the intensity (1-dim, 2-off, 3-bright).

Purpose: To write characters on the screen.

1 *SUBROUTINE TABLE FOR BASIC

2	EXTRN	DVM	
3	DC	1002.A(DVM),0	
4	EXTRN	PLOTR	
5	DC	1003.A(PLOTR),3	
6	EXTRN	DUMP	
7	DC	1005.A(DUMP),0	
8	EXTRN	LOOK	
9	DC	1006.A(LOOK),0	
10	EXTRN	SIDES	
11	DC	1007.A(SIDES),2	
12	EXTRN	SLAP	
13	DC	1008.A(SLAP),3	
14	EXTRN	STRT	
15	DC	1020.A(STRT),3	
16	EXTRN	HALT	
17	DC	1021.A(HALT),0	
18	EXTRN	RESUME	
19	DC	1022.A(RESUME),0	
20	EXTRN	TOGGLE	
21	DC	1023.A(TOGGLE),0	
22	EXTRN	DATA	
23	DC	1024.A(DATA),1	
24	EXTRN	ERROR	
25	DC	1026.A(ERROR),1	

0046R 0001
 0048R
 0048R 03E9
 0048R 0000F
 004CR 0006
 004ER

26
 27
 28

EXTRN WRITE
 DC 1001,A(WRITE),6

END

0 SQUEZ PASSES

NO ERRORS
COLR03

ABSTOP

ADC

> DATA

> DUMP

> DVM

> ERROR

> HALT

ITPTOP

LADC

> LOOK

> PLOTR

PURETOP

> RESUME

> SIDES

> SLOP

> STRT

> TOGGLE

> WRITE

0000

0002

003ER

000ER

0002R

0044R

002CR

004ER

0001

0014R

0000R

0000R

0032R

0010R

0020R

0026R

0030R

0040R

PA I

PROG= *NONE* 03-066R03M96

0000R
0000R

0000	0000
0000	0001
0000	0002
0000	0003
0000	0004
0000	0005
0000	0006
0000	0007
0000	0008
0000	0009
0000	000A
0000	000B
0000	000C
0000	000D
0000	000E
0000	000F
0000	00F0
0000	008C
0000	0000
0000	000E

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
CROSS	EXTRN	ENTRY	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW	EQW
R0	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	SDA	ADDA	HCHAN	RETURN			

PLOT1, MANY, P1, IX, P1, FLOAT
 STRT, HALT, TOGGLE, DVM, DATA, ERROR, SIDES, SLAP, RESUME

	S	E	L	C	H	D	E	V	I	C	E	A	D	D	R	E	S	S
	A	T	O	D	D	E	V	I	C	E	A	D	D	R	E	S	S	
	N	U	M	B	E	R	O	F	C	H	A	N	N	E	L	S		

```

25 *THIS ROUTINE BEGINS DATA COLLECTION FROM THE A TO D
26 *CALL IS OF THE FORM CALL 1020,H,01(0),B2(0)
27 *WHERE
28 * N IS THE NUMBER OF HALFWORDS IN EACH BUFFER
29 * B1 & B2 ARE ARRAYS, TO BE USED AS BUFFERS.
30 * EACH N HALFWORDS LONG
31 * (A REAL NUMBER IS USUALLY 2 HALFWORDS)
32 *THE ROUTINE ZEROS THE CHANNELS
33 *GET PARAMETERS
34     EQU 9
35     EQU 10
36     EQU 8
37     STH 0,R1020
38     STE 0,FR
39     LN 0,0(15)
40 *SET UP INTERRUPT HANDLER FOR SELCH
41     LHI R2,1SR
42     STH R2,2*SDA+X'D0'
43 *ZERO OUT THE CHANNELS
44     LHI R2,0
45     LHI R3,0
46     LHI R5,NCHAN-1*2
47     LHI R4,2
48     STH R2,CHANL(R3)
49     BXLE R3,ZLOOP
50 *SET UP ADDRESSES
51     LE 0,0(N)
52     BAL R15,MPIX
53     AHR R0,R0
54     SIS R0,1
55     STH BUF1,ASFB
56     AHR BUF1,R0
57     STH BUF1,AEFB
58     STH BUF2,ASOB
59     AHR BUF2,R0
60     STH BUF2,NEOB
61 *START UP SELCH, RETURN
62     BAL 14,RESUME
63     LE 0,FR
64     LN R0,R1020
65     BR RETURN
66     R1020 DSH 16
67     ASFB DS 2
68     AEFB DS 2
69     ASOB DS 2
70     AEOB DS 2
71 *CHANNELS
72     CHANL DSH NCHAN
73     R1022 DSH 16
74     FR DSF 1

```

0000 0009
 0000 000A
 0000 0000
 0000 0050R
 0004R 6000 1004R
 0008R D18F 0000

 000CR C820 10D8R
 0010R 4020 02B0

 0014R C820 0000
 0018R C830 0000
 001CR C850 0FTE
 0020R C040 0302
 0024R 4023 00B2R
 0028R C130 0024R

 002CR 6808 0000
 0030R 41F0 0000F
 0034R 0A00
 0036R 2701
 0038R 4090 007AR
 003CR 0A90
 003ER 4090 007CR
 0042R 4000 007ER
 0046R 0A00
 0048R 4000 0080R

 004CR 41E0 1008R
 0050R 6800 1004R
 0054R D100 0050R
 0058R 030E
 005AR
 007AR
 007CR
 007ER
 0080R

 0082R
 1082R
 1004R

STORE REGISTERS
 LOAD PARAMETER ADDRESSES
 PLACE ADDRESS OF INTERRUPT SERVICER
 IN INTERRUPT SERVICE TABLE

 START FOR BXLE
 INCREMENT FOR BXLE
 ZERO OUT CHANNEL

 CONVERT N
 RESULT RETURNED IN REG 0
 DOUBLE IT TO GET NO. BYTES

 SET UP FIRST BUFFER

 SET UP OTHER BUFFER

 START OF BUFFER BEING FILLED
 END OF BUFFER BEING FILLED
 START OF OTHER BUFFER
 START OF OTHER BUFFER

 THE CHANNELS

```

76 *THIS ROUTINE RESUMES DATA COLLECTION
77 *CALL IS OF THE FORM CALL I022
78 RESUME STM
79 LHI SELCH,SDA
80 AD,ADDA
81 *START SELCH
82 LHI R2,X'2000'
83 EPSR R3,R2
84 OC SELCH,SSSTOP
85 OC AD,HALF
86 LHI SELCH,ASF0
87 LHI SELCH,AEF0
88 RIR AD,R5
89 OC SELCH,SREAD
90 EPSR R2,R3
91 LHI 0,R1022
92 BR RETURN

```

```

10A0R D000 1002R
10A0R C0F0 00F0
10B0R C0E0 008C
10B4R C020 2000
10B8R 9532
10BA R DEF0 110FR
10BE R DEE0 110ER
10C2R D0F0 007AR
10C6R D0F0 007CR
10CA R 99E5
10CCR DEF0 1190R
10D0R 9523
10D2R D100 1002R
10D6R 030E

```

LOAD A TO D DEVICE ADDRESS

SHUT OFF
 INTERRUPTS
 STOP SELCH
 TELL INTERFACE THIS IS HALWORD TYPE
 GIVE STARTING AND ENDING ADDRESSES
 READ TO INITIALIZE DEVICE
 START SELCH

RETURN TO CALLER

```

94 *INTERRUPT SERVICE ROUTINE FOR SELCH
95 *PROCESSING DONE WITH INTERRUPTS DISABLED
96 *WISH TO FINISH DATA PROCESSING BEFORE USING NEW DATA
97 BEGIN EQU 11
98 END EQU 13
99 SELCH EQU 15
100 AD EQU 14
101 ISR DSF 1
102 OPSWA EQU ISR+2
103 DC X'2000'
104 STM 12,REGS+2
105 LHI SELCH.SDA
106 OC SELCH.SSTOP
107 *READ SELCH FINISHING ADDRESS
108 RIIR SELCH,R13
109 *START SELCH READ
110 OC SELCH.SSTOP
111 WH SELCH.ASOB
112 WH SELCH.AEOB
113 LHI AD.ADDA
114 SSR AD,R12
115 OC SELCH.SREAD
116 *STORE MORE REGISTERS
117 STH R11,REGS
118 *ERROR ON SELCH?
119 CH R13,AEFB
120 BE LCK
121 LIS R2,1
122 STH R2,SFLAG
123 LPSW ISR
124 *POSSIBILITY OF LOST DATA?
125 LCK LH R12,OPSWA
126 CH R12,ACONT
127 SWE NORMAL
128 LHI R12,X'0001'
129 STH R12,LOST
130 B TRUCK
131 NORMAL STH R12,PSWHOLD+2
132 LH R12,ISR
133 STH R12,PSWHOLD
134 *SWITCH BUFFERS
135 TRUCK LH BEGIN.ASF0
136 LH R12.ASOB
137 STH BEGIN.ASOB
138 STH R12.ASF0
139 LH END.AEF0
140 LH R12.AEOB
141 STH END.AEOB
142 STH R12.AEF0
143 *ACCUMULATE THE DATA

```

0000 0000
 0000 0000
 0000 000F
 0000 000E
 10D8R
 0000 10DAR
 2000
 10DCR
 10DER 00C0 1106R
 10E2R 08F0 00F0
 10E6R DEF0 110FR
 10EAR 99FD
 10ECR DEF0 110FR
 10F0R 08F0 007ER
 10F4R 08F0 0080R
 10F8R 08E0 00BC
 10FCR 9DEC
 10FER DEF0 1190R
 1102R 4000 1104R
 1106R 4900 007CR
 110AR 4330 1110R
 110ER 2421
 1110R 4020 117ER
 1114R C200 10D8R
 1118R 40C0 10DAR
 111CR 49C0 1176R
 1120R 4230 1130R
 1124R 00C0 0001
 1128R 40C0 117CR
 112CR 4300 113CR
 1130R 40C0 1102R
 1134R 40C0 10D8R
 1138R 40C0 1100R
 113CR 4000 0070R
 1140R 40C0 007ER
 1144R 4000 007ER
 1148R 40C0 0070R
 114CR 40D0 007CR
 1150R 40C0 0080R
 1154R 40D0 0080R
 1158R 40C0 007CR

OLD PSW STATUS PART
 OLD PSW ADDRESS PART
 NEW PSW STATUS PART, INTERRUPTS DISABLE
 STORE REGS 12-15
 CLEAR SELCH FOR COMMANDS
 CLEAR SELCH FOR COMMANDS
 SEND STARTING AND
 ENDING ADDRESSES
 LOAD A TO D DEVICE ADDRESS
 TO ADDRESS DEVICE
 START SELCH
 DID IT STOP AT END?
 SET ERROR FLAG
 RETURN TO INTERRUPTEE
 CHECK IF WE CAME FROM CONTINUE
 SET LOST DATA FLAG
 STORE AWAY CALLERS PSW

115CR	24C2	144	HEART	LIS	12,2	LOAD INCREMENT FOR BXLE
115ER	24E1	145		LIS	R14,1	
1160R	40FD 0000	146	LOOP	LH	R15,0(11)	LOAD DATA POINT
1164R	61EF 0002R	147		AM	R14,CHAH(15)	INCREMENT NEW LOCATION
1168R	C100 1160R	148		BXLE	11,LOOP	
		149	*RESTORE REGISTERS			
116CR	D180 1184R	150		LM	11,REGS	
1170R	C200 1174R	151		LPSW	ENABLE	BRANCH TO CONTINUE, ENABLE INTERRUPTS
1174R	6000	152	ENABLE	DC	X'6800'	
1176R	1178R	153	ACONT	DC	0(CONTINUE)	
1178R	C200 1180R	154	CONTINUE	LPSW	PSWOLD	
117CR	0000	155	LOST	DC	11'0'	RETURN TO CALLER
117ER	0000	156	SFLAG	DC	11'0'	
1180R		157	PSWOLD	DSF	1	
1184R		158	REGS	DS	10	
118ER	00	159	HALF	DB	X'A0'	
118FR	08	160	SSTOP	DB	X'08'	
1190R	30	161	SREAD	DB	X'30'	

1192R	D000	1226R	163	*CLOSE BUFFERS EARLY ROUTINE
1196R	C8F0	00F0	164	*CODE SIMILAR TO INTERRUPT SERVICE ROUTINE
119AR	C8E0	000C	165	*SUBROUTINES NOT MADE, HOWEVER, IN ORDER TO
119ER	CA20	2000	166	* RESTART SELCH AS QUICKLY AS POSSIBLE
11A2R	9532		167	CLOSER STM 0,CREGS
11A4R	9DF5		168	STORE REGISTERS
11A6R	4380	121ER	169	LOAD SELCH DEVICE ADDRESS
11A8R	4B50	1246R	170	LOAD A TO D DEVICE ADDRESS
11AER	4230	11C0R	171	SHUT OUT INTERRUPTS
			172	SEE IF SELCH IS BUSY
			173	IF NOT BUSY, DO NOTHING
			174	FIND OUT WHETHER TO RESTART
			175	REST
			176	*STOP SELCH
11B2R	DEF0	11BFR	177	SELCH,SSTOP
11B6R	99F0		178	SELCH,R0
11B8R	DEF0	11BFR	179	READ FINISHING ADDRESS
11BCR	4300	11D0R	180	RESET SELCH
			181	MERGE
11C0R	DEF0	11BFR	182	*STOP SELCH, RESTART
11C4R	99F0		183	REST
11C6R	DEF0	11BFR	184	SELCH,SSTOP
11CAR	D8F0	007ER	185	SELCH,R0
11CER	D8F0	0080R	186	OC
11D2R	99EC		187	WH
11D4R	DEF0	1190R	188	WH
			189	SELCH,ASOB
			190	SELCH,AE0B
			191	AD,R12
			192	SELCH,SREAD
			193	*CLEAR THE INTERRUPT WE CAUSED
11D8R	9F45		194	MERGE
11DAR	0B44		195	AIR R4,R5
11DCR	4230	11D0R	196	LHR R4,R4
			197	MERGE
11E0R	4B00	007CR	198	*SWITCH BUFFERS
11E4R	4B00	0080R	199	LH
11E8R	4B00	0080R	200	END,AEFB
11ECR	40C0	007CR	201	LH
11F0R	4B80	007AR	202	R12,AE0B
11F4R	4B00	007ER	203	END,AE0B
11F8R	4B00	007ER	204	STH
11FCR	40C0	007AR	205	STH
			206	R12,AEFB
			207	BEGIN,ASFB
			208	LH
			209	R12,ASOB
			210	STH
			211	BEGIN,ASOB
			212	R12,ASFB
				*FIND ENDING ADDRESS
1200R	2701			STH
1202R	C600	0001		R0,1
1206R	0B00			STIS
				OH1
				R0,X'0001'
				END,R0
				*ACCUMULATE DATA
1208R	090D			CHR
120AR	4380	121ER		BEGIN,END
120ER	24C2			BHL
1210R	24E1			RCLOSE
1212R	4BFB	0000		LIS
1216R	617C	0082R		12,2
				R14,1
				R15,0(11)
				R14,CHANL(R15)
				LOOP1
				LH
				AIM
				LOAD INCREMENT FOR 0XLE
				LOAD DATA POINT
				INCREMENT TALLY

1210R C100 1212R
 1211R 9523
 1220R D100 1226R
 1224R 030E
 1225R
 1245R 0000

213
 214 *RETURN TO CALLER
 215 RCLOSE EPSR R2-R3
 216 LM 0-CREGS
 217 BR 14
 218 CREGS DS 32
 219 RESTART DC X'0000'

BXLE 11,1,00PI

221 *THIS ROUTINE HALTS A DATA COLLECTION, TEMPORARILY
 222 *CALL IS OF THE FORM CALL 1021
 223 HALT STM 0,R1021 STORE REGISTERS
 224 LIS R2,0
 225 STH R2,RESTART SET RESTART FLAG
 226 BAL 14,CLOSER CALL CLOSER
 227 LM 0,R1021
 228 BR RETURN
 229 R1021 16

124BR D000 125CR
 124CR 2420
 124ER 4020 124ER
 1252R 41E0 1192R
 1256R D100 125CR
 125AR 030E
 125CR

231 *THIS ROUTINE SWITCHES DATA COLLECTION BUFFERS AND CONTINUES
 232 *CALL IS OF THE FORM CALL 1023
 233 *IT'S MAIN USE IS TO DUMP OUT DATA WHICH HAS BEEN COLLECTED BY
 234 * THE SELCH TO THE REAL WORLD FOR IMPATIENT PEOPLE LIKE ME
 235 TOGGLE STM 0,R1021 STORE REGISTERS
 236 LIS R2,1
 237 STM R2,RESTART SET RESTART FLAG
 238 BAL 14,CLOSER CALL CLOSER
 239 LM 0,R1021
 240 BR RETURN

127CR D000 125CR
 1280R 2421
 1282R 4020 1246R
 1286R 41E0 1192R
 1280R D100 125CR
 128ER 030E

```

242 *THIS ROUTINE READS A VALUE FROM THE A TO D AND DISPLAYS IT
243 *CALL IS OF THE FORM CALL 1002
244 *A HALT(CALL 1021) SHOULD BE ISSUED BEFORE THIS CALL
245 DVM STM 0,R1002
246 LHI AD,ADDA
247 LIS R0,1
248 DC R0,HEXON
249 DC AD,HALF
250 RIR AD,R3
251 SRLS R3,2
252 EXOR R3,R3
253 WIR R0,R3
254 LI 0,R1002
255 AR RETURN
256 HEXON DB X'00'
257 R1002 DSH 16

```

```

1290R D000 1202R
1291R C0E0 008C
1292R 2401
1293R DE00 1200R
1294R DEE0 110ER
1295R 99E3
1296R 9032
1297R 9433
1298R 9003
1299R D100 1202R
1200R 030E
1201R 80
1202R

```

SET THE DISPLAY PANEL
 TRIGGER A TO D, SET HALFWORD MODE
 READ VALUE
 CHUCK 2 LSB
 SWAP BYTE ORDER
 DISPLAY IT
 RETURN

```

259 *THIS ROUTINE TAKES THE CHANNELS AND PLUNKS THEM OUT TO AN ARRAY
260 *CALL IS OF THE FORM CALL 1024,C(0)
261 *WHERE C IS DIMENSIONED C(1023)
262 *(THE ROUTINE CONVERTS TO R*4 ON THE WAY)
263 C      EQU      B
264 DATA 0,R1024      STORE REGISTERS
265      LM      0,0(15)  LOAD PARAMETER ADDRESSES
266      LHI     R7,X'4600'  LOAD TOP HALF
267      LIS     R1,0      LOAD START FOR BXLE
268      LIS     R2,4      LOAD INCREMENT
269      LHI     R3,NCHAN-2*2
270      LH      R6,CHANL(R1)
271      NH      R6,CHANL+2(R1)
272      STH     R7,0(C)
273      STH     R6,2(C)
274      AIS     C,4
275      BXLE    1,DLOOP
276      LM      0,R1024
277      BR      RETURN
278      R1024  DSH      16

```

```

0000 0000
0000 1302R
12D2R D10F 0000
12D6R C070 4600
12D0R 2410
12DER 2424
12E0R C030 0FFC
12E2R 4061 0082R
12E6R 4061 0084R
12E0R 4070 0000
12F2R 4060 0002
12F6R 2604
12F0R C110 12E6R
12F0R D100 1302R
1300R 030E
1302R

```

200 *THIS ROUTINE CHECKS FOR VARIOUS ERROR CONDITIONS

201 *CALL IS OF THE FORM CALL 1026,E

202 *E WILL BE SET TO

203 * 0-NO ERRORS

204 * 1-ERROR ON SELECTOR CHANNEL

205 * 2-POSSIBILITY OF DATA LOSS

206 * 3-CHANNEL OVERFLOW

207 *ERROR CONDITIONS ARE CLEARED

0000 0000

1322R 0000 136CR

1326R 018F 0000

1320R C070 4600

132ER 4070 0000

1332R 2470

1334R 4060 117CR

1338R 2336

1330R 4070 117CR

133ER 2472

1340R 4300 1362R

1344R 4060 1630R

1348R 2336

1340R 4070 1630R

134ER 2473

1350R 4300 1362R

1354R 4060 117ER

1358R 4330 1362R

135CR 4070 117ER

1360R 2471

1362R 4070 0002

1366R D100 136CR

136AR 030E

136CR

STORE REGISTERS
LOAD PARAMETER ADDRESSES

INITIALLY SET TO 0

RESET

RESET

RESET

RETURN

```

316 *THIS ROUTINE SETS UP THE MARGIN DISPLAY
317 *CALL IS OF THE FORM CALL 1007,P(1),N
318 *WHERE P IS AN ARRAY OF Y-VALUES TO BE PLOTTED ON THE
319 *LEFT SIDE OF THE DISPLAY
320 *N IS THE DIMENSION OF P (DIM P(N)), N LESS THAN 50
321 P      EQU      0
322 PN     EQU      9
323 SIDES  STM      0,R1007
324        STE      0,F1007
325        LM       0,0(15)
326        LE       0,0(PN)
327        BAL      R15,FX
328        CLH      0,50
329        BL       POK
330
331 POK     LHI      0,50
332        STH      0,NSIDE
333        *CONVERT THE P ARRAY
334        LIS      5,2
335        LIS      6,2
336        LIH      7,0
337        AIR      R7,R7
338        LE       0,0(P)
339        BAL      R15,FX
340        STH      0,SIDE-2(5)
341        AIS      P,4
342        BXLE     5,MLOOP
343
344        *RETURN
345        LM       0,R1007
346        LE       0,F1007
347        BR       RETURN
348
349        SIDE     50
350        NSIDE    1
351        R1007    16
352        F1007    1

```

STORE REGISTERS

LOAD PARAMETER ADDRESSES

CONVERT DIMENSION

RESULT IN REG 0

CHECK IF ABOVE 50 (OR NEGATIVE)

IF ABOVE SET TO 50

SAVE IT AWAY

START FOR BXLE

INCREMENT FOR BXLE

ENDING FOR BXLE

LOAD NUMBER

CONVERT IT

STORE IT AWAY

```

351 *THIS ROUTINE PLOTS THE CHANNELS
352 *CALL IS OF THE FORM CALL 1000,S1,S2,I
353 *WHERE A CALL TO 1007 HAS PREVIOUSLY BEEN MADE
354 * S1 IS THE STARTING CHANNEL TO BE PLOTTED
355 * S2 IS THE ENDING CHANNEL TO BE PLOTTED
356 * I IS THE INTENSITY
357 *IT IS WRITTEN IN ASSEMBLER SOLELY TO AVOID
358 * LARGE SCALE USE OF OPERATIONS WHICH ARE SOFTWARE
359 * SIMULATED (LE M1 TO NAME TWO)
360 S1 EQU 8
361 S2 EQU 9
362 INT EQU 10
363 SLAP STM 0,R1007
364 STE 0,F1007
365 LM 0,0(15)
366 LE 0,0(INT)
367 BAL R15,FIX
368 STH 0,BRIGHT
369 LE 0,0(S1)
370 BAL R15,FIX
371 LHR S1,0
372 LE 0,0(S2)
373 BAL R15,FIX
374 LHR S2,0
375 *EQUATES FOR THE SPECIFIC DISPLAY
376 LEASTX EQU -2047
377 MOSTX EQU 2047
378 MARGINX EQU 100
379 LEASTY EQU -1638
380 MOSTY EQU 1638
381 MARGINY EQU 0
382 *CALCULATE X START AND X INCREMENT
383 XSTART EQU 11
384 XINC EQU 12
385 LHI XSTART,LEASTX+MARGINX
386 LIS R4,0
387 LHI R5,-2*MARGINX+MOSTX-LEASTX
388 LHR R6,S2
389 SHR R6,S1
390 AIS R6,1
391 DHR R4,R6
392 LHR XINC,R5
393 *DOUBLE THE STARTING AND ENDING FOR INDEXING
394 AHR S1,S1
395 AHR S2,S2
396 *MAKE A QUICK COPY OF THE CHANNELS, FOR THEY CONSTANTLY CHANGE
397 LHR R5,S1
398 LIS R6,2
399 LHR R7,S2
400 LHR R2,S1

```

```

0000 0000
0000 0009
0000 000A
1460R 0000 143AR
1464R 6000 145CR
1468R D10F 0000
146CR 680A 0000
1470R 41F0 138ER
1474R 4000 1626R
1478R 6808 0000
147CR 41F0 1472R
1480R 0000
1482R 6809 0000
1486R 41F0 147ER
1490R 0000
FFFF F801
0000 07FF
0000 0064
FFFF F99A
0000 0666
0000 0000
0000 000B
0000 000C
148CR C0B0 F865
1490R 2440
1492R C050 0F36
1496R 0869
1498R 0868
149AR 2661
149CR 0D46
149ER 08C5
14A0R 0A8B
14A2R 0A99
14A4R 085B
14A6R 2462
14A8R 0879
14AA R 0P~?

```

140CR	0A22	401	AIR	R2,R2	INDEX FOR CHANNELS
140ER	4B42 0002R	402	LH	R4,CHANL(R2)	COPY
1402R	4A42 00B4R	403	AI	R4,CHANL+2(R2)	SUM ADJACENT CHANNELS
1406R	2624	404	AIS	R2,4	
1408R	4045 1632R	405	STH	R4,COPY(R5)	
148CR	C150 140ER	406	DXLE	5,SLOOP	
		407	*SET UP FOR PLOT		
	0000 0002	408	XV	2	
	0000 0003	409	YV	3	
14C0R	2400	410	PL		RESET FLAG
14C2R	4000 162CR	411	LIS	R0,0	
14C6R	4000 162ER	412	STH	R0,PHALF	
14CAR	C8F0 161CR	413	LHI	R0,BUMPS	
14CER	0858	414	LHR	R15,P1	
14D0R	0879	415	LIR	R5,S1	
14D2R	082B	416	LIR	R7,S2	
14D4R	4020 1622R	417	STH	XV,XSTART	
14D8R	0A2C	418	AIR	XV,XVAL	TAKE CARE OF X
14DAR	4B35 1632R	419	LH	XV,XINC	
14DER	4210 15B2R	420	BN	YV,COPY(R5)	LOAD THE Y VALUE
14E2R	4330 14ECR	421	MORE	CRASH	CHECK FOR OVERFLOW OF A CHANNEL
14E6R	2401	422	LIS	SCALE	
14E8R	4000 162ER	423	STH	R0,1	WILL SET FLAG IF WE GET A NON ZERO VALU
		424	*SCALE THE YVALUES	R0,BUMPS	TO TELL IF WE HAVE THE ZERO FUNCTION
14ECR	4B10 162AR	425	SCALE		
14F0R	4000 162BR	426	LH	R1,CONS	
14F4R	4230 1500R	427	BNZ	R0,LEFT	CHECK IF WE'RE SHIFTING LEFT
14F8R	CE31 0000	428	SR	SL	
14FCR	4300 1504R	429	B	YV,0(R1)	
1500R	CF31 0000	430	SL	BUZZ	
1504R	CA30 F99A	431	BUZZ	YV,0(R1)	
		432	*CHECK FOR TOO BIG	YV,LEASTY+MARGINY	
1508R	C930 0566	433	CHI		
150CR	4280 151CR	434	DL	YV,MOSTY-MARGINY	
1510R	4000 1620R	435	LH	LITTLE	
1514R	4230 15E2R	436	BNZ	R0,LEFT	CHECK IF WE'RE SHIFTING LEFT
1518R	4300 15CCR	437	B	DEC	YES,MAKE IT SHIFT LESS
		438	*CHECK IF ANY MAKE IT OVER HALFWAY	INC	NO, SHIFTING RIGHT, MAKE IT SHIFT MORE
151CR	C930 0000	439	LITTLE	YV,MOSTY+LEASTY/2	(SOME SHOULD)
1520R	4280 152AR	440	BL	HOPE	
1524R	2401	441	LIS	R0,1	SET FLAG, WE'RE FINE
1526R	4000 162CR	442	STH	R0,PHALF	
		443	*ACTUAL PLOT		
152AR	4030 1624R	444	NOPE	YV,YVAL	
152ER	41E0 0000F	445	BAL	R14,PLOT1	
1532R	C150 14D4R	446	DXLE	R5,SLOOP	
		447	*POST MOTEM,	CHECK IF ANY BIG ENOUGH	
1536R	4000 162CR	448	LH	R0,PHALF	
153AR	4230 1552R	449	BNZ	DOMARG	
153ER	4000 162ER	450	LH	R0,BUMPS	NONE WERE BIG ENOUGH, BUT

1542R	4330	1552R	BZ	DOMARG	IF ZERO FUNCTION, OK
1546R	4800	1620R	LH	R0,LEFT	CHECK IF WE'RE SHIFTING LEFT
1540R	4230	15CCR	BNZ	INC	YES, MAKE IT SHIFT MORE
154ER	4300	15E2R	B	DEC	NO, SHIFT LESS
1552R	2452		*PLOT MARGINS		
1554R	4070	1430R	DOMARG	LIS	START FOR BXLE
1558R	4320	1509R	LH	R7,HSIDE	GET NO. POINTS
155CR	0077		BNP	RSLAP	IF NONE, RETURN
155ER	C800	F801	BNR	R7,R7	DOUBLE IT
1562R	4000	1622R	LH1	R0,LEASTX	
1566R	C0F0	161CR	STH	R0,XVAL	SET X COORDINATE
156AR	4035	1302R	LH1	R15,P1	SET UP FOR CALL
156ER	4010	162AR	LH	R3,SIDE-2(R5)	PICK UP POINT
1572R	4800	1628R	LH	R1,CONS	LOAD AMOUNT TO SHIFT
1576R	2135		LH	R0,LEFT	SHIFT LEFT?
1578R	CE31	0000	BNZS	MSL	
157CR	4300	1592R	SRHA	R3,0(R1)	SHIFT RIGHT
1580R	2420		B	HOP	
1502R	EF21	0000	LIS	R2,0	SHIFT LEFT
1505R	0822		SLA	R2,0(R1)	
1588R	4230	15A4R	LHR	R2,R2	IF OVERFLOW, DO NOT PLOT
158CR	0033		BNZ	SKIP	
158ER	4320	15A4R	LHR	R3,R3	
1592R	C030	F99A	BNP	SKIP	
1596R	4030	1624R	BN1	R3,LEASTY+MARGINY	
159AR	C930	0666	SAH	R3,YVAL	
159ER	2303		CHI	R3,MOSTY-MARGINY	CHECK IF OFF SCREEN
1500R	41E0	1530R	BNLS	SKIP	FORGET IT IF SO
15A4R	C150	156AR	0AL	R14,PLOT1	PLOT IT
1508R	D100	1430R	BXLE	5,MLOOP1	
150CR	6000	145CR			
1580R	030E				
1582R	C830	7FFF	MSR		
1586R	4800	1630R	MSL		
1500R	4230	14E2R	LH	0,R1007	SET TO LARGEST NUMBER
158ER	41E0	1240R	LE	0,F1007	CHECK IF FLAG UP
15C2R	2401		BR	RETURN	IF ALREADY UP, CONTINUE
15C4R	4000	1630R	*OVERFLOW OF A CHANNEL		
15C8R	4300	14E2R	LH1	YV,X'7FFF'	IF NOT, SET FLAG, AND ABORT
15CCR	4800	162AR	LH	R0,OVER	
15D0R	2601		BNZ	MORE	
15D2R	4000	162AR	0AL	I4,HALT	
15D6R	C900	0010	LIS	R0,1	
15DAR	4300	15F4R	STH	R0,OVER	
15DER	4300	1600R	B	MORE	
			*INCREMENT SHIFTER		
			INC	LH	R0,CONS
			AIS	R0,1	
			STH	R0,CONS	
			CHI	R0,X'0010'	IF MORE THEN 4 BITS BIG, TAKE ACTION
			BNL	FLIP	PLOT OUT THESE POINTS, AND START OVER
			B	CANCEL	
			*DECREMENT SHIFTER		
					129

15E2R	4000	1620R	501	DEC	LI	R0,CONS	
15E6R	2701		502		SIS	R0,1	
15E8R	4320	15F4R	503		BHP	FLIP	
15ECR	4000	1620R	504		STH	R0,CONS	
15F0R	4300	1608R	505		B	CANCEL	START OVER
			506	*DRASTIC	ACTION		
15F4R	2400		507	FLIP	LIS	R0,0	
15F6R	4000	1620R	508		STH	R0,CONS	
15F8R	4000	1620R	509		LI	R0,LEFT	
15FER	4330	1612R	510		AZ	LOH	
1602R	2400		511		LIS	R0,0	
1604R	4000	1628R	512		STH	R0,LEFT	TURN OFF LEFT SHIFT
1608R	2400		513	CANCEL	LIS	R0,0	KILL PLOT DUFFER
1600F	4000	0000F	514		STH	R0,MANY	
160ER	4300	1400R	515		B	PL	
1612R	2401		516	LOH	LIS	R0,1	TURN ON LEFT SHIFT
1614R	4000	1628R	517		STH	R0,LEFT	
1618R	4300	1400R	518		B	PL	
161CR	1622R		519	P1	DC	A(XVAL),A(YVAL),A(BRIGHT)	
161ER	1624R						
1620R	1626R		520	XVAL	DSH	1	
1622R			521	YVAL	DSH	1	
1624R			522	BRIGHT	DSH	1	
1626R			523	LEFT	DC	H'1'	
1628R	0001		524	CONS	DC	H'10'	
1620R	000A		525	PIALF	DSH	1	
162CR			526	BUMPS	DSH	1	
162ER			527	OVER	DC	H'0'	
1630R	0000		528	COPY	DSH	NCHAN	
1632R			529		END		
2632R							

[illegible]

PROG= *NONE* 03-066R03M96

0000R
0000R

0000 0000
0000 0001
0000 0002
0000 0003
0000 0004
0000 0005
0000 0006
0000 0007
0000 0008
0000 0009
0000 000A
0000 000B
0000 000C
0000 000D
0000 000E
0000 000F
0000 000E

1
2
3
4 R0
5 R1
6 R2
7 R3
8 R4
9 R5
10 R6
11 R7
12 R8
13 R9
14 R10
15 R11
16 R12
17 R13
18 R14
19 R15
20 RETURN

CROSS
ENTRY
ENTRY
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU
EQU

0
1
2
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14

MAHY
PLOT1,PLOTR,DUMP,LOOK,MFIX,MFLOAT,WRITE

```

22 *THIS ROUTINE PLOTS AN X&Y PAIR AT A CERTAIN INTENSITY
23 *CALL IS OF THE FORM CALL 1003,X,Y,I
24 *WHERE
25 * X & Y ARE THE X AND Y VALUES. IN THE RANGE -2047 TO 2047
26 * VALUES OUTSIDE THIS RANGE GIVE BIZARRE RESULTS
27 * I IS THE INTENSITY
28 * I=DIH
29 * 2=OFF (VERY BORING)
30 * 3=BRIGHT
31 *THE ROUTINE HAS ENTRIES FOR R*4 ARGUMENTS (NS FROM A NORMAL
32 * BASIC CALL) AND I*2 ARGUMENTS
33 *THE ROUTINE DUMPS POINTS TO THE DISPLAY WHENEVER ITS BUFFER
34 * ITS BUFFER IS FILLED. THE BUFFER CAN BE DUMPED BY THE USER
35 * WITH A CALL 1005
36 *IN THE CASE THAT THE NEW X VALUE IS THE SAME AS THE OLD, THE
37 * ROUTINE ONLY SOCKS AWAY A Y COORDINATE
38 X EQU 8
39 Y EQU 9
40 I EQU 10
41 BSIZE EQU 4096
42 *R*4 DATA ENTRY
43 PLOTR STH 0,R1003
44 LM 0,0(15)
45 LE 0,0(X)
46 BAL 15,MFIX
47 LHR X,0
48 LE 0,0(Y)
49 BAL 15,MFIX
50 LHR Y,0
51 LE 0,0(I)
52 BAL 15,MFIX
53 LHR I,0
54 B PLOT
55 *I*2 DATA ENTRY
56 PLOTI STH 0,R1003
57 LM 0,0(15)
58 LH X,0(X)
59 LH Y,0(Y)
60 LH I,0(I)
61 *ALTER DATA INTO 12 BIT TWO'S COMPLEMENT
62 PLOT LHR X,X
63 BP CHECKY
64 AHI X,4096
65 CHECKY LHR Y,Y
66 BP INTEN
67 AHI Y,4096
68 INTEN MHI X,X'0FFF'
69 MHI Y,X'0FFF'
70 *PUT IN INTENSITY
71 SLS I,12

```

0000 0000
 0000 0009
 0000 0000
 0000 1000
 0000 0002R
 0004R 010F 0000
 0008R 6000 0000
 000CR 41F0 21C8R
 0010R 0800
 0012R 6009 0000
 0016R 41F0 21C8R
 001AR 0890
 001CR 6000 0000
 0020R 41F0 21C8R
 0024R 08A0
 0026R 4300 003ER
 002AR 0000 00A2R
 002ER 010F 0000
 0032R 4000 0000
 0036R 4099 0000
 003AR 400A 0000
 003ER 0800
 0040R 4220 0040R
 0044R CA00 1000
 0040R 0899
 004AR 4220 0052R
 004ER CA90 1000
 0052R C400 0FFF
 0056R C490 0FFF
 005AR 91AC

STORE REGISTERS
 LOAD PARAMETER ADDRESSES
 CONVERT X
 CONVERT Y
 CONVERT INTENSITY
 STORE REGISTERS
 LOAD PARAMETER ADDRESSES
 LOAD VALUES
 IF NEGATIVE, ADD 4096
 MAKE SURE

INTENSITY INTO FIRST HIDDLE
MARK AS A Y POINT

INCREMENT COUNT

DOUBLE

INCREMENT COUNT

005CR	0690	005CR	0690	4000	72	OUR	Y, I
005ER	C690	005ER	C690	4000	73	OH1	Y, X' 4000'
0062R	4980	0062R	4980	00C2R	74	*PLACE IN X POINT, IF NOT A REPEAT	
0066R	4330	0066R	4330	007ER	75	CH	X, LASTX
0060R	4000	0060R	4000	00C2R	76	BE	PLACEY
006ER	4850	006ER	4850	00C4R	77	STH	X, LASTX
0072R	2651	0072R	2651		78	LI	5, MANY
0074R	4050	0074R	4050	00C4R	79	ATS	5, I
0078R	9151	0078R	9151		80	STH	5, MANY
007AR	4085	007AR	4085	00C6R	81	SLLS	5, I
007ER	4050	007ER	4050	00C4R	82	STH	X, BUFFER-2(5)
0082R	2651	0082R	2651		83	*PLACE IN Y POINT	
0084R	4050	0084R	4050	00C4R	84	PLACEY	LI
0088R	9151	0088R	9151		85	ATS	5, MANY
008AR	4095	008AR	4095	00C6R	86	STH	5, MANY
008ER	C050	008ER	C050	00FF	87	SLLS	5, I
0092R	4950	0092R	4950	00C4R	88	STH	Y, BUFFER-2(5)
0096R	2123	0096R	2123		89	*TIME TO DUMP?	
0098R	41E0	0098R	41E0	20C8R	90	LHI	5, BSIZE-1
009CR	D100	009CR	D100	00A2R	91	CH	5, MANY
00A0R	030E	00A0R	030E		92	BPS	RPL0T
00A2R	FFFF	00A2R	FFFF		93	BAL	14, DUMP
00C2R	0000	00C2R	0000		94	*RETURN	
00C4R	0000	00C4R	0000		95	LM	0, R1003
00C6R	0000	00C6R	0000		96	OR	RETURN
00C8R		00C8R			97	DSH	16
					98	DC	X'FFFF'
					99	DC	X'0000'
					100	DC	X'0000'
					101	DSH	BSIZE

103	0000 0004	*THIS ROUTINE DUMPS THE PLOT BUFFER TO THE DISPLAY	
104	0000 0008	*CALL IS OF THE FORM CALL 1005	
105	0000 000C	*CURRENTLY;	
106	20C8R	* NBS BUS SHOULD BE LOGICAL UNIT 0	
107	20CCR 40F0 00C4R	* D TO A SHOULD BE SUBADDRESSES 4&5	
108	20D0R 033E	* MEMORY SHOULD BE SUBADDRESS 6&7	
109	20D2R 24E0	DTA EQU 4	
110	20D4R 40E0 00C4R	BUSLU EQU 8	
111	20D6R 4300 20E6R	HEH EQU 6	
112		*DUMP RESETS THE BUFFER	
113		DUMP STM 0,R1005	STORE REGISTERS
114		LH R15,MANY	GET COUNT
115		BZR 14	IF NOTHING TO DO, DO NOTHING
116		LIS R14,0	ZERO OUT COUNT
117		STH R14,MANY	
118		B LUMP	
119		*LOOK DOES NOT RESET THE BUFFER	
120	20DCR 0000 21A8R	LOOK STM 0,R1005	STORE REGISTERS
121	20E0R 48F0 00C4R	LH R15,MANY	GET COUNT
122	20E4R 033E	BZR RETURN	
123		*REPLICATE DATA, AS MANY TIMES AS POSSIBLE	
124	20E6R 0AFF	LUMP AHR R15,R15	DOUBLE COUNT
125	20E8R C8E0 2000	LH1 R14,2*BSIZE	LOAD TWICE BUFFERSIZE
126	20ECR 24C0	LIS R12,0	SET UP FOR DIVIDE
127	20EER 08DE	LHR R13,R14	
128	20F0R 0DCF	DHR R12,R15	
129	20F2R 0CCF	MHR R12,R15	
130	20F4R C8C0 00C8R	LH1 R12,BUFFER	STARTING POINT OF BUFFER
131	20F8R CAE0 00C8R	AH1 R14,BUFFER	ENDING POINT OF BUFFER
132	20FCR CAF0 00C8R	AH1 R15,BUFFER	STARTING POINT OF REPLICATION
133	2100R CAD0 00C8R	AH1 R13,BUFFER	ENDING POINT OF REPLICATION
134	2104R 09FD	FILL CHR R15,R13	AT END OF REPLICATION?
135	2106R 4300 211AR	BHL BLANK	
136	210AR 48BC 0000	LH R11,0(R12)	LOAD A POINT
137	210ER 40BF 0000	STH R11,0(R15)	COPY IT
138	2112R 26C2	AIS R12,2	INCREMENT COUNTER
139	2114R 26F2	AIS R15,2	
140	2116R 4300 2104R	B FILL	
141		*BLANK OUT REST OF BUFFER	
142	211AR 2400	BLANK LIS R11,0	
143	211CR 09DE	FILLB CHR R13,R14	AT END OF BUFFER?
144	211ER 4300 212CR	BHL BUSC	
145	2122R 40BD 0000	STH R11,0(R13)	
146	2126R 26D2	AIS R13,2	INCREMENT COUNT
147	212OR 4300 211CR	B FILLB	
148		*NOTE EVERY TIME THE BUS IS RESTARTED	
149	212CR E110 2176R	BUSC SVC L,UP	TURN ON BUS
150	2130R E110 217AR	SVC L,COM	SELECT COMMAND ADDRESS SUBADDRESS
151	2134R E110 217ER	SVC L,ACT	SEND COMMAND
152	2138R E110 2188R	SVC L,MCOM	SELECT MEMORY COMMAND SUBADDRESS

213CR	E110 210CR	153		SVC	1,MACT	SEND COMMAND
		154	*THIS BLOCK WRITE SHOULD BE UNDER SVC			
		155	*YOU'RE RIGHT, THERE IS A BLOCK WRITE UNDER SVC			
		156	*BUT AT THIS TIME IT IS DEAD			
	0000 0000	157	NBSBUS EQU X'00'			
2140R	C0F0 0000	158	LHI 15,NBSBUS			
2144R	DEF0 2196R	159	OC 15,SCOUNT			
2140R	DAF0 2197R	160	WD 15,ME			
2140R	DEF0 21A2R	161	OC 15,SUB			
2150R	40E0 21A4R	162	LH R14,START			
2154R	9DF0	163	SSR R15,R13			
2156R	4200 2154R	164	BTC 0,WAIT			
2150R	D0FE 0000	165	WJ R15,0(R14)			
2150R	26E2	166	AIS R14,2			
2160R	49E0 21A6R	167	CH R14,STOP			
2164R	4200 2154R	168	BL WAIT			
		169	*TURN ON AND GO			
2160R	E110 2100R	170	SVC 1,MCOM			
2160R	E110 2190R	171	SVC 1,MGO			
		172	*RETURN			
2170R	D100 21A0R	173	LM 0,R1005			
2174R	030E	174	BR RETURN			
		175	*PARAMETER BLOCKS			
2176R	9400	176	UP X'9400'+BUSLU 1001 0100			
2170R	C500	177	DS 2			
2170R	C500	178	COM DTA+1*256+X'C000'+BUSLU			
2170R	2000	179	DS 2			
2170R	2000	180	ACT X'2000'+BUSLU 0010 1000			
2180R	2106R	181	DS 2			
2180R	2107R	182	DC A(CON),A(CON+1)			
2106R	0077	183	ON X'0077'			
2100R	C700	184	MCOM MEM+1*256+X'C000'+BUSLU			
2100R	2000	185	DS 2			
2100R	2000	186	MACT X'2000'+BUSLU 0010 1000			
2100R	2194R	187	DS 2			
2192R	2195R	188	DC A(MON),A(MON+1)			
2194R	0001	189	MON X'0001'			
2196R	03	190	SCOUNT X'03'			
2197R	06	191	ME MEM			
2190R	2000	192	MGO X'2000'+BUSLU 0010 1000			
2190R	21A0R	193	DS 2			
2190R	21A1R	194	DC A(MUNGO),A(MUNGO+1)			
2100R	0002	195	MUNGO X'0002'			
2102R	20	196	SUB X'20'			
2104R	00C6R	197	START A(BLOCK)			
2106R	20C7R	198	STOP BSIZ+2+1+BLOCK			
2108R		199	R1005 16 138			

SELECT THE SUBADDRESS COUNTER
SELECT THE MEMORY SUBADDRESS
SELECT SUBADDRESS MODE

IF BUSY, WAIT
WRITE AN ELEMENT

SELECT MEMORY COMMAND SUBADDRESS

201	*THIS ROUTINE CONVERTS A R*4 NUMBER TO I*2	
202	*CALL: BAL 15,MFIX	
203	*INPUT: IN FLOATING POINT REGISTER 0	
204	*OUTPUT: IN REGISTER 0	
205	*NUMBERS IN THE RANGE -32767 TO 32767 ARE CONVERTED CORRECTLY	
206	MFIX STN 0,RF	STORE REGISTERS
207	AE 0,UNCON	ADD UNNORMALIZED ZERO
208	STE 0,WORK	STORE AWAY, STILL UNNORMALIZED
209	LH 14,WORK	LOAD FIRST PART
210	BMS NEG	IS NUMBER NEGATIVE?
211	LH 0,WORK+2	NO, WE'RE OK
212	0 RMFIX	
213	LH 0,WORK+2	
214	XHI 0,X'FFFF'	COMPLEMENT IT
215	ALS 0,1	
216	RMFIX LM 1,RF+2	LOAD REGISTERS
217	DR 15	
218	RF DSH 16	
219	WORK DSF 1	
220	UNCON DC X'4600',X'0000'	
221	*THIS ROUTINE CONVERTS A I*2 NUMBER TO R*4	
222	*CALL: BAL 15,MFLOAT	
223	*INPUT: REG 0	
224	*OUTPUT: FLOATING POINT REGISTER 0	
225	MFLOAT STN 0,RF	STORE REGISTERS
226	LHR 0,0	
227	BMS IIEG1	IS NUMBER NEGATIVE?
228	STH 0,PLUS+2	NO, FINE
229	LE 0,PLUS	
230	0 RMFLOAT	COMPLEMENT IT
231	NEGI XHI 0,X'FFFF'	
232	ALS 0,1	
233	STH 0,MINUS+2	
234	LE 0,MINUS	
235	RMFLOAT LM 0,RF	
236	BR 15	
237	PLUS DC X'4600',0	
238	MINUS DC X'C600',0	
239	LAST NOPR 0	

241	0000 0009	*THIS ROUTINE PLOTS A CHARACTER STRING	
242	0000 0007	* CALL IS OF THE FORM CALL 1001,S\$,X,Y,XI,YI,I	
243	0000 0009	*WHERE	
244	0000 0004	* S\$ IS THE STRING TO BE WRITTEN AT	
245	0000 0002	* COORDINATES X&Y (X & Y BETWEEN -2047 AND 2047)	
246	0000 0008	* XI&YI ARE THE SPACINGS BETWEEN THE POINTS	
247	0000 0009	* THESE GOVERN THE SIZE AND SHAPE OF THE CHARACTERS	
248	0000 000A	* I IS THE INTENSITY, I=DIM,3=BRIGHT	
249	0000 000B	HIGH EQU 9	
250	0000 000C	WIDE EQU 7	
251	0000 000D	SEP EQU 9	
252	0000 000E	CHAR EQU 4	
253	0000 000F	BIT EQU 2	
254	0000 0010	STRING EQU 0	
255	0000 0011	X EQU 9	
256	0000 0012	Y EQU 10	
257	0000 0013	XI EQU 11	
258	0000 0014	YI EQU 12	
259	0000 0015	I EQU 13	
260	0000 0016	WRITE EQU 0,R1001	
261	0000 0017	STE EQU 0,F1001	
262	0000 0018	LM EQU 8,0(15)	
263	0000 0019	LE EQU 0,0(X)	
264	0000 001A	BAL EQU R15,MFIX	
265	0000 001B	LHR EQU X,R0	
266	0000 001C	LE EQU 0,0(Y)	
267	0000 001D	BAL EQU R15,MFIX	
268	0000 001E	STH EQU R0,YB0SE	
269	0000 001F	LE EQU 0,0(XI)	
270	0000 0020	BAL EQU R15,MFIX	
271	0000 0021	LHR EQU XI,R0	
272	0000 0022	LE EQU 0,0(YI)	
273	0000 0023	BAL EQU R15,MFIX	
274	0000 0024	LHR EQU YI,R0	
275	0000 0025	LE EQU 0,0(I)	
276	0000 0026	BAL EQU R15,MFIX	
277	0000 0027	STH EQU R0,IP	
278	0000 0028	*STEP THROUGH THE STRING	
279	0000 0029	L15 EQU R5,I	
280	0000 002A	L15 EQU 6,I	
281	0000 002B	L0 EQU R7,-1(STRING)	
282	0000 002C	LHR EQU R7,R7	
283	0000 002D	BZ EQU RWRITE	
284	0000 002E	L0 EQU CHAR,0(STRING)	
285	0000 002F	LHR EQU R3,TABLE	
286	0000 0030	CL0 EQU CHAR,0(R3)	
287	0000 0031	BE EQU PLOTTT	
288	0000 0032	AHI EQU R3,SEP	
289	0000 0033	CLHI EQU R3,EOTABLE	
290	0000 0034	BL EQU SEARCH	
224ER	0000 2338R		LOAD PARAMETER ADDRESSES
2252R	0000 2358R		LOAD PARAMETER X
2256R	018F 0000		
2258R	0009 0000		
225ER	41F0 21C8R		LOAD PARAMETER Y
2262R	0090 0000		
2264R	680A 0000		
2268R	41F0 21C8R		LOAD PARAMETER XI
226CR	4000 232AR		
2270R	6000 0000		
2274R	41F0 21C8R		LOAD PARAMETER YI
2278R	0000 0000		
227AR	680C 0000		
227ER	41F0 21C8R		LOAD PARAMETER I
2282R	00C0 0000		
2284R	680D 0000		
2288R	41F0 21C8R		
228CR	4000 2330R		
2290R	2451		LOAD START FOR BXLE
2292R	2461		LOAD INCREMENT FOR BXLE
2294R	D378 FFFF		LOAD LENGTH OF STRING
2298R	0B77		
229AR	4330 22C4R		
229ER	D340 0000		LOAD CHARACTER
22A2R	C830 235CR		LOOK IN TABLE FOR CHARACTER
22A6R	D443 0000		FOUND IT?
22AAR	4330 22CER		
22AER	C430 0009		
22B2R	C530 2526R		END OF TABLE
22B6R	4200 2206R		

220AR	2601	HEXT	01S	STRING.1	GO ON TO NEXT CHARACTER
220CR	0A9A	291	AIR	X.X1	SPACE TO NEXT CHAR
220ER	0A9B	292	AIR	X.X1	
220GR	C150	293	BXLE	5.LOOP	
220HR	229ER	294			
220IR	D100	295	*RETURN		
220JR	2330R	296	RWRITE	LM 0.R1001	
220KR	0800	297	LE	0.F1001	
220LR	030E	298	BR	14	
220MR	2631	299	*PLOT A CHARACTER		
220NR	2420	300	PLOTTT	01S R3.1	POINT TODATA TABLE
220OR	4B00	301		BIT.0	BIT POINTER
220PR	232AR	302	HXTCOL	Y.YBASE	
220QR	0A9A	303		X.X1	INCREMENT X
220RR	24D1	304		R13.1	COUNTER FOR Y
220SR	41F0	305	MORE	BAL R15.RETRIEVE	CHECK THE BIT
220TR	4330	306		BZ	IF OFF, NO PLOT
220UR	4090	307		STH X.XP	
220VR	40A0	308		STH Y.YP	
220WR	08F0	309		LHI R15.PARBLK	
220XR	2332R	310		BAL R14.PLOT1	
220YR	41E0	311	SKIP	01S	NEXT BIT
220ZR	2621	312		CHI	AT END OF CHAR?
220AR	C920	313		BP	
220BR	4220	314		01S R13.1	
220CR	26D1	315		CHI R13.HIGH	AT TOP OF CHARACTER?
220DR	C9D0	316		OP HXTCOL	
220ER	4220	317		AIR Y.Y1	INCREMENT Y
220FR	0AAC	318		B	
220GR	4300	319		MORE	
220HR	22DAR	320			
220IR		321			
220JR		322			
220KR		323			
220LR		324			
220MR		325			
220NR		326			
220OR		327			
220PR		328			
220QR		329			
220RR		330			
220SR		331			
220TR		332			
220UR		333			
220VR		334			
220WR		335			
220XR		336			
220YR		337			
220ZR		338			
220AR		339			
220BR		340			
220CR		341			
220DR		342			
220ER		343			
220FR		344			
220GR		345			
220HR		346			
220IR		347			
220JR		348			
220KR		349			
220LR		350			
220MR		351			
220NR		352			
220OR		353			
220PR		354			
220QR		355			
220RR		356			
220SR		357			
220TR		358			
220UR		359			
220VR		360			
220WR		361			
220XR		362			
220YR		363			
220ZR		364			
220AR		365			
220BR		366			
220CR		367			
220DR		368			
220ER		369			
220FR		370			
220GR		371			
220HR		372			
220IR		373			
220JR		374			
220KR		375			
220LR		376			
220MR		377			
220NR		378			
220OR		379			
220PR		380			
220QR		381			
220RR		382			
220SR		383			
220TR		384			
220UR		385			
220VR		386			
220WR		387			
220XR		388			
220ZR		389			
220AR		390			
220BR		391			
220CR		392			
220DR		393			
220ER		394			
220FR		395			
220GR		396			
220HR		397			
220IR		398			
220JR		399			
220KR		400			
220LR		401			
220MR		402			
220NR		403			
220OR		404			
220PR		405			
220QR		406			
220RR		407			
220SR		408			
220TR		409			
220UR		410			
220VR		411			
220WR		412			
220XR		413			
220ZR		414			
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220NR		428			
220OR		429			
220PR		430			
220QR		431			
220RR		432			
220SR		433			
220TR		434			
220UR		435			
220VR		436			
220WR		437			
220XR		438			
220ZR		439			
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220OR		454			
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220QR		456			
220RR		457			
220SR		458			
220TR		459			
220UR		460			
220VR		461			
220WR		462			
220XR		463			
220ZR		464			
220AR		465			
220BR		466			
220CR		467			
220DR		468			
220ER		469			
220FR		470			
220GR		471			
220HR		472			
220IR		473			
220JR		474			
220KR		475			
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220MR		477			
220NR		478			
220OR		479			
220PR		480			
220QR		481			
220RR		482			
220SR		483			
220TR		484			
220UR		485			
220VR		486			
220WR		487			
220XR		488			
220ZR		489			
220AR		490			
220BR		491			
220CR		492			
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220GR		496			
220HR		497			
220IR		498			
220JR		499			
220KR		500			
220LR		501			
220MR		502			
220NR		503			
220OR		504			
220PR		505			
220QR		506			
220RR		507			
220SR		508			
220TR		509			
220UR		510			
220VR		511			
220WR		512			
220XR		513			
220ZR		514			
220AR		515			
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220MR		527			
220NR		528			
220OR		529			
220PR		530			
220QR		531			
220RR		532			
220SR		533			
220TR		534			
220UR		535			
220VR		536			
220WR		537			
220XR		538			
220ZR		539			
220AR		540			
220BR		541			
220CR		542			
220DR		543			
220ER		544			
220FR		545			
220GR		546			
220HR		547			
220IR		548			
220JR		549			

233BR		339	R1001	DSH	16	
235BR		340	F1001	DSF	1	
235CR	41FE0084	341	TABLE	DB	C'A',X'FE',X'00',X'84',X'22',X'11',X'00',X'88',X'F8'	
	2211088B					
	F8					
236SR	42FFC462	342		DB	C'B',X'FF',X'C4',X'62',X'31',X'18',X'8C',X'45',X'DC'	
	31188C45					
	DC					
236ER	437F4060	343		DB	C'C',X'7F',X'40',X'60',X'30',X'18',X'0C',X'05',X'04'	
	30180C05					
	04					
2377R	4480FFE0	344		DB	C'D',X'80',X'FF',X'E0',X'30',X'18',X'00',X'08',X'F8'	
	30180A08					
	F8					
2380R	45FFC462	345		DB	C'E',X'FF',X'C4',X'62',X'31',X'18',X'0C',X'46',X'02'	
	31188C46					
	02					
2389R	46FF8442	346		DB	C'F',X'FF',X'84',X'42',X'21',X'10',X'08',X'44',X'02'	
	21100844					
	02					
2392R	477F4060	347		DB	C'G',X'7F',X'40',X'60',X'30',X'19',X'0C',X'87',X'C4'	
	30190C87					
	C4					
2398R	48FF8402	348		DB	C'H',X'FF',X'84',X'02',X'01',X'00',X'07',X'FC',X'00'	
	010087FC					
	00					
23A4R	49000020	349		DB	C'I',X'80',X'00',X'20',X'3F',X'F8',X'08',X'00',X'00'	
	3FF80800					
	00					
23ADR	4A404020	350		DB	C'J',X'40',X'40',X'20',X'10',X'17',X'F8',X'04',X'00'	
	1017F804					
	00					
23B6R	40FF8405	351		DB	C'K',X'FF',X'84',X'05',X'04',X'44',X'14',X'04',X'00'	
	04441104					
	00					
23BFR	4CFFC020	352		DB	C'L',X'FF',X'C0',X'20',X'10',X'00',X'04',X'00',X'00'	
	10000400					
	00					
23C0R	40FF8080	353		DB	C'M',X'FF',X'80',X'00',X'00',X'80',X'20',X'08',X'FE'	
	80802008					
	FE					
23DIR	4EFF8101	354		DB	C'N',X'FF',X'81',X'01',X'01',X'01',X'01',X'03',X'FE'	
	01010103					
	FE					
23DAR	4F7F4060	355		DB	C'O',X'7F',X'40',X'60',X'30',X'18',X'08',X'F8',X'00'	
	301808F8					
	00					
23E3R	5000FFC2	356		DB	C'P',X'00',X'FF',X'C2',X'21',X'10',X'88',X'44',X'1C'	
	21100844					
	1C					

23ECR	517F4060 34140DF0 00	357	DB	C'Q',X'7F',X'40',X'60',X'34',X'14',X'0D',X'F0',X'00'
23FSR	52FF0446 25140C30 00	358	DB	C'R',X'FF',X'04',X'46',X'25',X'14',X'0C',X'30',X'00'
23FER	53474462 31100000 00	359	DB	C'S',X'47',X'44',X'62',X'31',X'10',X'00',X'00',X'00'
2407R	54000040 3FF00004 02	360	DB	C'T',X'00',X'00',X'40',X'3F',X'F0',X'00',X'04',X'02'
2410R	557FC020 100003FC 00	361	DB	C'U',X'7F',X'C0',X'20',X'10',X'00',X'03',X'FC',X'00'
2419R	5603000C 10030060 0E	362	DB	C'V',X'03',X'06',X'0C',X'10',X'03',X'00',X'60',X'0E'
2422R	577FC020 0E00401 FE	363	DB	C'W',X'7F',X'C0',X'20',X'0E',X'00',X'04',X'01',X'FE'
2420R	50C19105 01014113 06	364	DB	C'X',X'C1',X'91',X'05',X'01',X'01',X'41',X'13',X'06'
2434R	59010101 1F004010 06	365	DB	C'Y',X'01',X'01',X'01',X'1F',X'00',X'40',X'10',X'06'
2430R	50C00064 31104C16 06	366	DB	C'Z',X'C0',X'D0',X'64',X'31',X'10',X'4C',X'16',X'06'
2446R	307F4062 309020F0 00	367	DB	C'0',X'7F',X'40',X'62',X'30',X'90',X'20',X'F0',X'00'
244FR	31000020 5FF00000 00	368	DB	C'1',X'00',X'00',X'20',X'5F',X'F0',X'00',X'00',X'00'
2450R	32C15064 31100C30 00	369	DB	C'2',X'C1',X'50',X'64',X'31',X'10',X'0C',X'30',X'00'
2461R	33414062 31100000 00	370	DB	C'3',X'41',X'40',X'62',X'31',X'10',X'00',X'00',X'00'
246AR	34301409 044217FC 00	371	DB	C'4',X'30',X'14',X'09',X'04',X'42',X'17',X'FC',X'00'
2473R	3547C261 309040C4 00	372	DB	C'5',X'47',X'C2',X'61',X'30',X'90',X'40',X'C4',X'00'
247CR	367F4462 31100000	373	DB	C'6',X'7F',X'44',X'62',X'31',X'10',X'00',X'00',X'00'

2485R	00	374	DB	C'7',X'E0',X'00',X'42',X'20',X'90',X'20',X'0C',X'00'
248ER	00	375	DB	C'0',X'77',X'44',X'62',X'31',X'10',X'00',X'00',X'00'
2497R	00	376	DB	C'9',X'07',X'44',X'62',X'31',X'14',X'09',X'F0',X'00'
2400R	00	377	DB	C',X'00',X'00',X'00',X'10',X'0C',X'00',X'00',X'00'
2409R	00	378	DB	C',X'00',X'00',X'20',X'0C',X'06',X'00',X'00',X'00'
2482R	00	379	DB	C'-',X'00',X'04',X'02',X'01',X'00',X'00',X'40',X'00'
2480R	00	380	DB	C'7',X'01',X'00',X'74',X'21',X'10',X'40',X'10',X'00'
24C4R	00	381	DB	C',X'00',X'00',X'00',X'00',X'00',X'00',X'00',X'00'
24CDR	00	382	DB	C',X'00',X'00',X'05',X'02',X'01',X'40',X'00',X'00'
24D6R	00	383	DB	X'23',X'14',X'00',X'1F',X'C2',X'07',X'F0',X'00',X'50'
24DFR	50	384	DB	C'(',X'00',X'00',X'0F',X'00',X'20',X'00',X'00',X'00'
24E0R	00	385	DB	C'),X'00',X'00',X'20',X'20',X'23',X'E0',X'00',X'00'
24F1R	00	386	DB	C'0',X'76',X'44',X'06',X'54',X'C4',X'05',X'00',X'00'
24F0R	04	387	DB	C',X'40',X'10',X'04',X'01',X'00',X'40',X'10',X'04'
2503R	00	388	DB	C':',X'00',X'00',X'00',X'06',X'C3',X'60',X'00',X'00'
250CR	00	389	DB	C'+',X'00',X'04',X'02',X'07',X'C0',X'00',X'40',X'00'
2515R	00	390	DB	C'*',X'00',X'11',X'05',X'01',X'01',X'41',X'10',X'00'

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251ER 270000000
007000000
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2520R

391 DB X'27',X'00',X'00',X'00',X'00',X'70',X'00',X'00',X'00'
392 EOTABLE EQU *-1
393 END

NO ERRORS 0 SQUEZ PASSES

CALR03

ADSTOP

ACT

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211AR

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00C8R

212CR

0008

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004AR

217AR

0004

20C8R

2526R

2358R

2104R

211CR

0009

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2528R

0052R

2330R

0001

224CR

00C2R

20DCR

229ER

20E6R

218CR

00C4R

2108R

2197R

0006

21C0R

221CR

2198R

2248R

2194R

2200R

21A0R

0008

21E2R

2230R

2280R

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301

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HXTCOL	22D2R	316							
ON	21B6R	102							
PARBLK	2332R	309							
PLACEY	007ER	76							
PLOT	003ER	54							
< PLOT1	0020R	310							
PLOTIT	22CER	207							
< PLOTR	0000R	220							
PLUS	2244R	229							
PURETOP	0000R								
R0	0000	265	268	271	274	277	330	331	332
R1	0001	322	324	325	328	329			
R10	000A								
R1001	233BR	260	296						
R1003	00A2R	43	56	95					
R1005	21A0R	113	120	173					
R11	000B	136	137	142	145				
R12	000C	126	120	129	130	136	138		
R13	000D	127	133	134	143	145	146		
R14	000E	116	117	125	127	131	143		
		327	327	332					
R15	000F	114	121	124	124	128	129	137	139
		267	270	273	276	305	309	162	167
		322	323					163	166
		205	206	208	209	300	326	165	165
		323	329	331				310	325
		279						134	163
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								312	312
								313	313
								314	314
								315	315
								316	316
								317	317
								318	318

Character strings in BASIC look like:

03 42 41 44 - - - - -.

The first byte (03) is the length of the string. The address passed in a call statement is the second byte which begins the string.

The characters are stored in a table. The first byte for each telling the character and the next 63 bits showing which parts of the 9 x 7 matrix are to be lit. The routine searches through the first bytes for all entries to find a match for the character at hand and then sends the coordinates of the points to be plotted to the plotting routine PLOTI. If a character is not found in the character table, no error is generated and that character is simply skipped.

The example below will illustrate how the values in the table were derived. Consider the letter A in a 7 x 9 matrix

```
bbxxbb
xbbbxb
xbbbbx
xbbbbx
xbbbbx
xxxxxx
xbbbbx
xbbbbx
xbbbbx .
```

The bits are arranged in order column by column starting at the bottom
xxxxxxx0 0000x000 x0000x00 00x000x0 000x000x 0000x000 x000x0xx xxxxx000
or in hexadecimal

FE 08 84 22 11 08 8B F8.

III. Appendix References

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* Certain commercial instruments are identified in order to adequately specify the results. In no case does such identification imply recommendation by the National Bureau of Standards, nor does it imply the instruments are the best available.

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* Certain commercial materials and electronic devices are identified in order to adequately specify the experimental results. In no case does such identification imply recommendation by the National Bureau of Standards, nor does it imply the material is the best available.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.) This final report describes the results of a four-year effort to study the high voltage dielectric behavior of various materials at cryogenic temperatures. Dissipation factors at 60 Hz were measured for polymer tapes and epoxy samples at 4.2 K, atmospheric pressure. Multi-layer polymer samples in coaxial geometries at temperatures from 7 to 10 K and helium pressures up to 1.5 megapascals were also studies. The measurements were performed at stresses up to 40 MV/m. Since partial discharges were a major source of losses at the higher stresses and their presence was possibly detrimental to the integrity of the insulation, instrumentation was developed and implemented to study these discharges under conditons found in proposed ac superconducting power-transmission lines.			
17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons) Capacitance; cryogenic; dielectric constant; dielectric properties; dissipation factor; electrical transmission; partial discharges; polymers; precision electric measurements; pulse-height-analysis; superconducting transmission			
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